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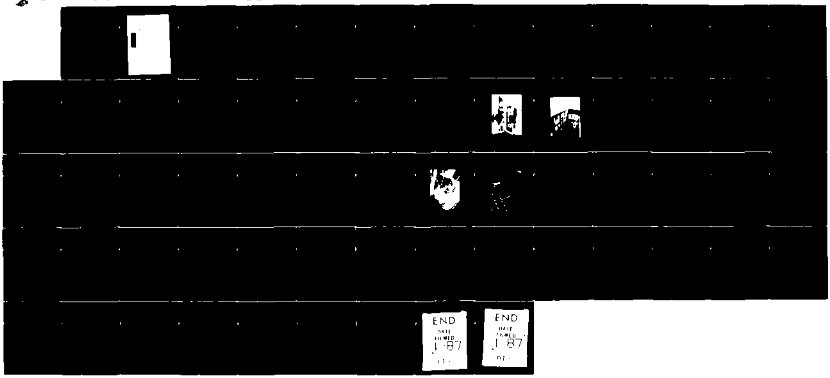

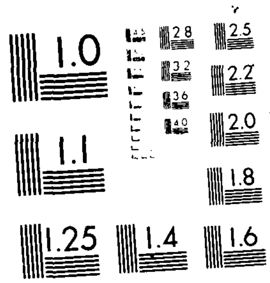

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THE ARE(GLEN FRUIN) DENSITY STRATIFIED TANK (U)

by

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Abstract

The conversion of an experimental tank at Glen Fruin into one of the world's largest stratified test facilities is described. The stages of development and the commissioning tests are reported. The tank is shown to offer a stable environment for research on buoyancy influenced flows with relatively weak density gradients and a relatively large cross section, (U)

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INTRODUCTION

Meteorologists, oceanographers and engineers have a considerable interest in fluids with small density variations that occur naturally in the atmosphere, oceans, lakes and reservoirs. If the density increases with depth or decreases with height, then the fluid is said to be stably stratified. It has long been recognized (1) that even small variations in the density can have important influences on flow behaviour and the dynamics of mixing processes. Although the fluid mechanics of stratified flows are complex, a better understanding will benefit prediction techniques describing the dispersion of pollutants in the atmosphere or coastal waters, the control of stratification in reservoirs to improve water quality, and the heat transfer processes both within and between the oceans and atmosphere leading to improved weather forecasting.

Much theoretical effort has been devoted to characterizing the effects of density stratification. Expressions for internal wave spectra have been developed (2), with good agreement for the deep ocean (500m+), but considerably more work is needed to achieve the same success for the shallower regions encompassing the seasonal pycnocline (typically 50-100m). The dynamics at the shallower depths are much more complex because of the larger number of sources associated with the air-sea interface. Also the modelling of the dissipation and decay of turbulence under the influence of stratification is relatively poorly developed.

Field experiments are both difficult and costly to set up, requiring vertical sensor arrays monitoring at a number of horizontal locations for long time periods. The large spatial and temporal variability of the ocean environment and the interaction of many processes (eg turbulence, internal waves and velocity shear) further complicate the interpretation of offshore trials data. Other natural facilities such as lakes and reservoirs, although offering reasonable scale testing, suffer from environmental forcing and the lack of controllability. For these reasons laboratory experiments have been designed to investigate ocean and atmospheric phenomena under controllable and reproducible conditions and to provide the stimulus for the development of theoretical models. However, it is not possible to model all the non-dimensional parameters relevant to natural systems and problems invariably arise because of difficulties in scaling parameters such as the Peclet and Reynolds numbers which may differ by orders of magnitude between laboratory and nature.

This note describes the development and commissioning of a density stratified tank at the Admiralty Research Establishment (ARE) site at Glen Fruin in Scotland. The decision to develop such a facility to support those ocean studies where density variations are important was made in 1979. No tank suitable for conversion existed at ARE(Teddington) and because of limited space, no tank could be built on site. Other local tanks were considered and rejected because of their size (either far too

large, such as towing tanks, or too small), because of the high cost of hiring a stratified tank which cannot be intermittently employed on other work usefully or because of difficulties in generating a stratified fluid (for example, corrosion or structural problems).

A tank at Glen Fruin was finally chosen because, at 9m x 3m x 3m, it permitted the investigation of phenomena of relatively large length scale; furthermore it was little used and could be allocated exclusively for stratified experiments as it was under the management control of ARE Teddington, and had good engineering facilities on site. However, the main disadvantage was that, at Glen Fruin, it would be situated some 500 miles from other complementary studies at Teddington.

Although development of this type of facility would be a new experience in the UK, large tanks had been successfully stratified in the USA. The tanks at the Environmental Protection Agency (EPA)(3) in N Carolina, measuring 25m long, 2.4m wide by 1.2m deep, and at the Flow Research Company (4), Kent, Washington, measuring 18m long, 1.2m deep, and 0.9m deep, are of comparable size. Likewise, it was decided to stratify the tank with saline solution, although much smaller water tanks (5) and a wind tunnel (6) have been thermally stratified. With large tanks the need to maintain consistent experimental conditions and to restrict the number of refills favours the use of salt because of its lower molecular diffusity than heat. In the ocean, however, density stratification invariably involves both temperature and salt distributions (with thermal changes dominating at the shallower depths producing thermoclines) in which double diffusive processes can produce 'steps' on the density profile.

Many towing tanks in which strict control of air and water temperature is not observed become thermally stratified with time. A linear variation of $0.5^{o}C$ over a depth of 2m produces a stratified environment with a natural frequency of approximately 5 minutes. For skin friction and wave resistance type measurements the additional energy loss through internal wave radiation could be significant in terms of the high degree of precision required, and may be an additional factor accounting for the variation of test results with standard models in different tanks worldwide (7).

Many experiments (8-10) have been conducted in relatively small tanks with a strong density gradient where buoyancy effects dominate. In the ocean many important transport and mixing processes occur where inertial and buoyancy forces are of similar order (ie a typical Richardson number for the flow may be of order unity or an internal Froude number may be $>>1$, but not infinite). For large physical scale experiments,this would be achieved by using either higher characteristic flow speeds, not always a practical method, or weaker density gradients.

Apart from the Glen Fruin tank having a larger cross section than either the EPA or Flow Research tanks (and therefore expecting to suffer less from boundary effects) the tank was designed from the outset to operate with relatively weaker density gradients. Whereas the EPA and Flow Research tanks

operate with density gradients in the range 18-176 kg m^{-4} and 36-100 kg m^{-4} respectively, the density gradient range planned for Glen Fruin was approximately 1-9 kg m^{-4}.

Dynamic effects in salt stratified tanks are usually measured by conductivity sensors where changes in conductance and displacement are related to the motion via the measured salinity profile. An assessment of the calibration and use of a particular conductivity sensor for the internal wave studies is given by Rodger (11). Weak density gradients with low concentrations of salt solution have an advantage in that the sensitivity of conductivity probes to changes in saline concentration are greater under these conditions. Furthermore, should the tank need to be refilled on a regular basis (the structure may have changed significantly over the course of an experimental programme) then, on a practical note, the quantity of salt required and the subsequent mixing and dissolution processes involved are much smaller and easier to achieve.

Although it was not possible to provide a closely controlled temperature environment for the tank, some limited temperature control was provided by the presence of a larger glass sided hydrodynamic test facility, containing about 4,000 m^3 of water, whose thermal inertia attenuates some of the fluctuations in temperature associated with the Scottish climate. This larger tank also provided a source of filtered water for the small stratified tank.

The requirement for weak density gradients coupled with the environmental influence posed questions about the stability of the stratification, once created. When the salinity gradient is weak only small temperature differences over the tank depth are necessary to either counteract this halocline or to produce an unstable profile. This problem would be expected to be exacerbated when the air temperature gradually decreased causing correspondng changes in the tank surface temperatures. Temperature changes in the body of the fluid could cause cell like flow structures to occur which, once initiated, would be very difficult to eradicate and would probably destroy the water structure in the process.

Figures 1 and 2 show the location of the tank and a close up prior to its modification. The tank is made of reinforced brick construction with one side and one end wall fitted with glass to permit observation.

One important experimental simplification made at Glen Fruin, and in many other laboratory studies of ocean phenomena, involves the removal of any background current shear as one of the parameters under investigation. Not only are stratified shear facilities very much more complex to build and maintain (to date this has only been achieved at relatively small scale (12, 13), but the shear interacts with other oceanographic processes with the result that interpretation and physical understanding of some processes is impaired. The inclusion of shear is usually a second stage investigation.

This report describes the results of initial small scale

experiments and the tank filling arrangement adopted. The commissioning tests that were performed and their results and conclusions are presented. The further modification needed to the tank and the stability of the profile is discussed.

2. STRATIFYING THE TANK

(a) Techniques

The prime requirement for the filling technique was that the tank should be able to be structured with an arbitrary density profile even though initial tests would be based upon a 3 layer sandwich, with a linear gradient region between two uniform density layers, as illustrated in Figure 3a. Figure 3b shows the corresponding natural buoyancy or Brunt-Vaisala frequency (N) which is related to the density gradient by $N^2 = -g/\rho\ (d\rho/dz)$, where ρ is the fluid density, g the gravitational acceleration and z the vertical direction (measured positively upwards). Tank filling procedures represent a compromise between the time taken to fill the tank and the need to avoid fluid mixing arising from too high fluid injection velocities.

Many different techniques for producing a density gradient have evolved over the years. Most are based upon the concept of introducing fluid at the bottom of the tank and slowly increasing the density of the fluid entering the tank. However a technique used by Kao and Pao (14), incorporating a float system and gradually introducing lighter density fluid, appears to work satisfactorily.

In the limit, a continuous density profile may be considered as being made up from an infinite number of very thin fluid layers, each with a density slightly less than the layer below. Many methods to produce continuous profiles have been based upon this principle. Some of the techniques are only practicable for relatively small scale operations.

A linear density gradient is a special case and is one that has been a popular choice amongst experimenters because it has been the profile assumed in many theoretical studies. The filling system described by Oster and Yamamoto (5) to produce a linear gradient was seen as a significant improvement over previous methods. The system, shown schematically in Figure 4 and described in Appendix I, is known as the 'two-bin' method and is a popular technique (10,16). This method has so simplified the production of a linear stratification using salt solution, that nearly every example found in the literature since 1965 has used an individual adaptation of it.

For structures more representative of the ocean seasonal thermocline Rouse and Dodu(7), Cromwell(8), and Turner (19) have found that turbulent mixing in the upper 'layers' and the entrainment caused, produced a sharpening of the density gradient. However, techniques based upon this concept are only considered practical for the smaller scale work.

More recently, automatic filling systems have been used especially where the tank is of reasonable capacity or requires

refilling frequently. Richards and Heather (20) describe two automatic systems, one based on an analogue method (using gate and mixture control valves operated through servomechanisms) and the other based upon a digital method with a numerically controlled metering pump. Measured density distributions were found to be within 0.02% of that desired for the analogue method and 0.01% for the digital method.

Before detailed design of a filling technique for Glen Fruin could proceed several questions needed to be answered. Firstly, it was necessary to know what fill rate, in terms of depth increase per hour, could be accepted without mixing. The critical control on filling time is the overall depth of fill. Non-turbulent filling can be maintained for any tank length or width by increasing the discharge rate proportionally through an increased number of distribution pipes. Secondly, and a procedure directly related to this first problem, is how the fluid should best be introduced into the tank. Thirdly, having introduced the fluid into the tank, how long would the profile remain stable. In discussing tank filling techniques, few authors indicate the duration of the original fill or whether any special precautions were taken to maintain it. With the relatively weak gradients required at Glen Fruin, diffusion processes were expected to be of little significance in modifying the profile.

Appendix II shows that for typical values of salinity gradient, the diffusion processes at Glen Fruin were expected to be extremely slow and would take many months to significantly modify profiles of this type. However, the relatively lower buoyancy forces made the Glen Fruin tank more susceptible to thermally induced mixing cells. This was seen as the major uncertainty affecting the tank stability.

Appendix III describes initial experiments performed in a small glass aquarium, 2m x 0.6m x 0.6m, in an attempt to find answers to the first two questions. Although weak gradients could be generated it was not possible to infer the long term stability of a weak density gradient in the large tank from a small tank in a laboratory where temperature could be controlled. Using the 'two-bin' stratifying process a method of introducing fluid into the tank at a rate of .16 m/hr without apparent mixing was devised.

Although the Flow Research tank (4) is filled using an elaborate version of the Oster concept (and storage space is saved by using the tank itself as a storage tank for fresh water before and during the fill) the capacity of the Glen Fruin tank, at 80 m^3, is four times larger and the 'two-bin' technique was judged to be impracticable because of the limited space to store the large quantities of brine and water required.

Also, because uncertainties remained after the initial experiments about the behaviour of the weakly stratified water, once subjected to the environment, it was decided that an automatic filling system would not be considered until the viability of the tank had been demonstrated and that the initial three-layer structure would be synthesised using a number of layers over the density gradient region.

(b) Method Adopted

A diagram of the salt mixing system is shown in Figure 5. Salt was mixed with fresh water in the mixing tank 'A' to form a brine solution with a specific gravity of approximately 1.07. Solutions of this concentration, which contain about 40% by weight of the salt needed to produce a saturated solution, were found to be easy to produce and handle. The brine solution was then pumped into the brine tank 'B'. A 'Fluidmix'unit (supplied by Bestobell Valves Ltd.) was mounted on the side of the fresh water supply tank 'C' (fitted with a level control) and which mixed the brine and water to the required solution for the experimental tank. Whilst the Fluidmix unit was being set to give the correct output, measured by a salinity probe (SP2), the waste solution was discharged into the calibration tank 'D'. When the salinity was correct and constant, valve V9 was opened and the solution could be directed either into the experimental tank via the flow meter or temporarily into storage tank 'E'.

Initial filling of the tank with fresh water could be achieved through flow meter FM1 and valve V4. The temperature fluctuation of the fresh water supplied from the larger adjacent 4000 m^3 tank was found to be minimal.

The salinity (and conductivity) of the solution required to generate a particular density was determined from tables (21) which present density as a function of temperature and salinity. The conductivity required was always related to a standard reference temperature because slight temperature excursions in the feed would diffuse out after the solution had been introduced into the tank. The relative effects of salinity and temperature gradients on the value of the buoyancy frequency are:-

for salinity, $N = .083\sqrt{(\Delta s/\Delta z)}$, where Δs is the change in salinity in parts per thousand and Δz is the vertical change. for temperature, the value of N is temperature dependent such that

$$N = .029\sqrt{(\Delta T/\Delta z)} \text{ at } 10^{\circ}C$$

$$N = .038\sqrt{(\Delta T/\Delta z)} \text{ at } 15^{\circ}C$$

where ΔT is the change in temperature over depth interval Δz.

These latter values are based on pure water expansion coefficients which are good approximations in view of the very weak salt solution considered at Glen Fruin.

In principle any density profile could be fabricated with this technique although the process would be lengthy. The solution entered the experimental tank through a distribution system of 12 plastic tubes (to avoid corrosion) equally spaced along the length of the tank and each spanning the width. Along the length of each tube, holes of 1.58mm diameter were drilled separated by 50.8mm, far enough to prevent intermixing.

The first test with this system generated a two-layer density structure in the tank with freshwater overlying a constant

density salt layer. Figures 6 and 7 show the effects of diffusion on the density and buoyancy profiles at approximately 3 weeks after filling. This structure was relatively easy and quick to produce, allowed appraisal of the Fluidmix units and after diffusion was complete, and provided an intermediate density gradient region for the initial tank characterization test (described in the next section).

However the Fluidmix units did not operate as well in this filling arrangement as expected, being the critical control variable in the filling rate, so the procedure was modified to the filling arrangement shown in Figure 8. The Fluidmix unit, the brine tank'B', supply tank 'C' and calibration tank 'D' were bypassed in the flow sequence. In all subsequent tank fills, a measured volume of brine of known salinity from the mixing tank 'A' was pumped direct to the storage tank 'E' to which fresh water was added, recirculated as shown, and adjusted until a completely mixed solution of the required salinity was achieved. The solution entered the experimental tank via the same distribution network as before. Should doping or dyeing of particular layers be required then this could easily be achieved with this arrangement.

Early density and buoyancy profiles obtained with the modified filling arrangement are shown in Figures 9 and 10 where the extent of the density gradient is approximately 1m. Eight intermediate layers of constant density were used to generate this gradient region as recommended by the initial small tank experiments. Although the density profile showed evidence of these layers just after filling, overnight diffusion had smoothed out the step-like structures. Mowbray (22) derived the theoretical timescale for the disappearance of these steps as a result of diffusion. He showed that the larger the number of layers used, the shorter was the time method for the system to diffuse into a smooth profile. However his observations, like the small tank tests, showed that the linear profiles were established more rapidly than the theoretical predictions. The small amount of mixing at each interface during filling, which smoothes out the initial discontinuities but which leaves the central region of the layers unaffected, accounts for the shorter timescales observed.

Up to 400kg of salt are required to obtain the three layer tank profile described earlier. The mixing tank with a capacity of 2 m^3 is not capable of holding all the salt required for a fill in solution. It is therefore customary to recharge the mixing tank about seven times for fills requiring the larger quantities of salt.

About four working days are typically required to complete a fill with the modified system. Although the small tank test showed that the maximum flow rate into the tank could be 0.16m depth per hour, the batchwise process used means that a much reduced overall rate is achieved. In practice, the maximum rate applies to the construction of variable density regions and when a large mixed layer is required, the flowrate can be increased once far enough away from the interface so that mixing is not likely to cause problems.

It is instructive to compare the filling characteristics used at Glen Fruin with the following stability criteria for a stratifying process obtained by Richards and Heather (20).

$$- \frac{g d\rho}{\rho dz} \left[LA/F\right]^2 \quad > O(1),$$

alternatively

$$\left[NLA/F\right]^2 \quad > O(1),$$

where N = buoyancy frequency (rad/s)
A = plan area of the tank (m^2)
F = total flowrate (m^3/s)
L = length scale of turbulence (= jet diameter) (m). Note that (F/A) = rate of increase of depth.

This inequality is based upon the assumption that the spectra of turbulent fluctuations of the velocity in the fluid entering the tank are independent of the total flowrate.

Using typical values for the Glen Fruin fill,

$A = 27m^2$
$N = .1$ rad/s
$L = 1.58 \times 10^{-3}$ m
$F = 1.2$ l/s $= 1.2 \times 10^{-3}$ m^3/s,

the value of the left hand side is 12.6; ie >O(1). Physically this relationship means that mixing will occur over a particular depth scale if, and only if, there is sufficient turbulent kinetic energy to create the consequent change in gravitational potential energy. Conversely, the lengthscale, L, can be derived for which the characteristics of the stratifying process are of order unity. In the Glen Fruin example the mixing lengthscale is expected to be of order 0.4mm. In a gradient region of approximately 1m this is not considered, nor indeed found, to be significant.

The tank density profile is measured using a double electrode conductivity sensor (Tacussel type CM0822G) coupled with a thermistor (Fenwall type GB42SMM1). Originally the profiles were measured at discrete intervals of 5cm throughout the 3m depth, but the sensors are now lowered into the tank over a pulley controlled by a stepper motor. Measurements are made at each step, which corresponds to a depth interval of 1mm. Details of this profiling arrangement are reported by Thomson (23).

3. TANK CHARACTERIZATION TESTS

With the diffused two-layer water structure obtained from the first fill, (see Figure 6), the first exercise undertaken was to investigate the behaviour and stability of the water column. A number of profiles were made with the combined conductivity and thermistor assembly at 9 prime locations around the tank. From these profiles, temperature and conductivity section plots were generated showing the variation around the tank at different levels (see Figure 11). The strong correlation of the variations of the conductivity and temperature in this plot is due to the temperature influence on conductivity. The relatively low air

temperature (4.5°C) resulted in an adverse destabilising temperature gradient. This temperature profile and the corresponding conductivity profile for the centre of the tank are shown in Figure 12. The abrupt change in the temperature profile almost coincident with the changes in the conductivity (density) profile indicates that large mixing cells were present in the upper and lower layers, with buoyancy forces limiting further transfer. Anomalies of this sort on temperature profiles invariably indicate the presence of internal cells.

Since the thermal boundary conditions on each wall of the tank were different (2 brick walls - one forming an outside wall; 2 glass-sided walls in different environments) additional temperature profiles were measured over the 9 locations shown in Figure 11 but as close to the walls as was practicable. The results showed significant differences, up to 1°C, from those obtained at the neighbouring station, indicating an appreciable heat transfer through the side boundaries.

The glass end and side walls of the tank proved invaluable during this test phase. To assist visualisation of the water movements, crystals of the fluorescent dye Rhodamine B were dropped into the tank. Rhodamine B crystals produce an intense dye streak which, because of the low molecular diffusivity of rhodamine, remains as a streak for a considerable time. This property, together with its fluorescent nature, makes it better suited for this type of work than potassium permanganate crystals.

Although movements within the stratified region were observed, the largest velocity, by far, corresponded to a maximum surface movement in excess of 3 cm/s. A number of thin plastic sheets, 2.5 cm square, were placed in the water surface and the positions of the 'floats' were recorded with time. A typical plot is shown in Figure 13. This two cell surface circulation pattern was a consistent feature of all the plots made and was no doubt a main contributor to upper layer mixing inferred from the temperature profiles.

Although the stratified tank was enclosed within the large observation area of the main tank, this surface drift was thought to be generated by a small air flow. Smoke tests confirmed the presence of such a flow and after further investigation this was considered to be part of a buoyancy driven flow associated with the temperature difference across the glass side of the adjacent large tank.

During tests with the dye crystals, anomalous flows were observed in the vicinity of the tank windows and, also, dye on the bottom of the tank, marking the initial crystal drop, gradually migrated towards one corner of the tank. Furthermore, local dye marking showed that the steel framework of the windows was responsible for a thermally driven flow. Further investigation identified the source of the flow in the lower layer as due to heat transfer along the reinforced structure from a small basement boiler situated some 10m distant in the direction of the flow and at a lower level than the tank. (Surprisingly, none of the investigators had been aware of the presence of this boiler).

Summarising, the tests highlighted the following causes of the internal flows in the tank:

a. surface draught, producing surface circulation patterns which influenced fluid motion in the upper layer;

b. heat transfer through the side walls, initiating buoyancy driven cells - local differences in overall heat transfer produce local flows - eg steel framework on windows;

c. heat flux from the small boiler inducing a flow in the lower layer.

In spite of these observed flows, throughout the test period the conductivity and density profiles, remained stable and surprisingly consistent.

4. REMEDIAL ACTION

To overcome the draught it was essential that the tank was fitted with its own cover, preferably transparent to ease the lighting problems for photographic and video work. A greenhouse frame was installed over the tank and covered with clear plastic sheeting. The limited space around the tank favoured the use of a flexible rather than a rigid sheet so that access through the sides was possible. This greenhouse type structure is shown in Figure 14. To help reduce draughts around the tank in general, a policy of strict control on the opening of the exterior doors of the tank area was introduced and all these doors were fitted with automatic closing mechanisms.

Removal of the temperature induced effects was recognised to be a more difficult problem. Temperature control of the immediate environment was not considered to be a practical proposition in view of the proximity of the larger tank. The roof insulation of the laboratory had however been recently renovated thus providing some thermal control. Heat transfer through the sides and bottom of the tank would be minimised by fitting a layer of insulation on the inside of the tank. However this meant that the large observation windows would be obscured, but under the circumstances there was no practical alternative. Heat transfer through the surface would be accepted, although the greenhouse cover would help to reduce some of the more rapid temperature fluctuations. Surface heat transfer was considered to be less of a problem with regard to internal flows than side wall transfer because of the upper layer 'buffer'.

The insulation chosen to cover the inside surfaces of the tank was a closed-cell rigid PVC foam material, type D40, 1.5 cm thick, which at $0.027 W/m^{o}C$ offered the lowest thermal conductivity. This material was supplied by the Plasticell Division of Permali Glouceser Ltd. The closed cell structure offers high thermal insulation, a quality which is retained when immersed in water. This feature also makes the material extremely buoyant and it therefore required strong fixing. The interior glass walls were first covered by sheets of marine ply* and the sheets of insulation were fixed to the marine ply and the brick wall by an adhesive, applied hot, recommended by Plasticell.

The D40 is supplied as a blue sheet and so, in order to provide a better background for photographic work and observation, the insulation was covered with a thin white plastic sheet. Figure 15 shows the interior of the tank (with the fluid distribution tubes) after fitting. To reduce further the heat loss through the glass walls, 10cm thick polystyrene sheets were fixed to the outer glass surfaces.

To reduce the effect from the small boiler, the inside of the boiler room was similarly covered with these D40 insulating sheets, suitably treated to minimise the fire hazard. To regain some observation capability in the tank, a small hole approximately 30cm square was cut from the insulation and marine ply at the end wall and a double glazed 'port hole' was inserted flush with the remaining insulation. Direct solar radiation, thought not to be a problem at Glen Fruin, was nevertheless eliminated from the tank by fitting window blinds.

Repeated tests when the tank was refilled following these modifications showed that these remedies had been successful. The profile shown in Figures 9 and 10 obtained with the modified filling procedure, also represented the first tank fill after these remedial actions. Surface currents were difficult to detect and internal flows, although not entirely eliminated, were significantly reduced. Dye tracks indicated a maximum velocity of approximately 10^{-6} m/s, which is small compared to internal wave propagation velocities (calculated from the dispersion relationship on an idealised typical tank profile) except for velocities corresponding to high wavenumbers (>100 rad/m) or to the high mode number (>20) case. For details see Appendix IV.

5. LONG TERM STABILITY OF THE TANK

One of the main uncertainties raised initially concerned the long term stablity of the tank. From the last section many of the modifications made to the tank helped to minimise the level of the environmental forcing although not removing all influences. Measurements of the conductivity and temperature profiles in the tank have been routinely made. Details of this data acquisition and conversion to density and buoyancy profiles are given by Thomson (23). It is obvious that the integrity of the tank structure depends upon the type and level of activity in the tank. Large scale (relative to the tank dimensions) mixing events are more likely to cause significant changes. The energy fed into the environment has to be dissipated. This usually results in the expansion of the mixed layers at the expense of the stratification. Small scale disturbances, producing turbulence and internal waves, are less likely to produce long lasting effects because the internal waves will ultimately dissipate and although turbulence will produce local mixing, diffusion and buoyancy act in time to repair the damage. Persistent disturbance of the same fluid volume may, however, not allow this to happen and more permanent profile scars will result.

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* Marine ply initially caused discolouration of the water due to leaching dye. After the third fill with thorough intermediate washing this dye presented no further problem.

Figures 16-19, reproduced from Thomson (23), show the salinity, temperature, density and buoyancy profiles taken over 13 weeks from an initial fill. Comparison of the salinity profiles reveals little change. The basic shape of the density profile has changed little over this timescale illustrating the relatively weaker influence of temperature on density and supporting the conclusion drawn earlier that diffusive processes alone are unlikely to have any significant effect with these weak gradients. The reduction in the buoyancy frequency value is due to the formation of a temperature profile which countered the salinity gradient. The uncorrected density and salinity profiles show a more obvious vertical shift due to the drop in surface level, of approximately 5 cms, as a result of evaporation. The datum for the profiler is the surface. The temperature profiles also show that the heat transfer into the tank primarily occurred through the surface, demonstrating the effectiveness of the insulation.

6. SUMMARY

Table 1 presents a brief summary of the characteristics of the Glen Fruin stratified facility.

The tests and measurements described show that the Glen Fruin tank is able to provide a large, controlled, stratified facility for long term work, subject to the type of experiment to be done. The features of particular note are its large size and the relatively weak density gradients which can be achieved. Many of the difficulties associated with the environment have been overcome and the results demonstrate the success of the remedial action following the initial characterization tests.

The size of the facility makes it one of the largest of its type in the world, with the particular advantage of having a large cross-section which, with the ability to maintain weaker density gradients than are commonly used, permits larger scale experiments to be conducted. Alternatively, the facility allows longer absolute data acquisition times because of the larger separation of the vertical and horizontal boundaries and because with weaker density gradient the internal wave propagation velocities are slower.

Although only one type of profile (a three-layer) has been considered here, in principle there is no reason why any arbitrary profile could not be installed. Although not considered at the outset, the successful development of the facility to date has encouraged studies evaluating an automatic stratifying process. This has resulted in the specification and order for a microprocessor-controlled blending pump. The options considered and the final specification are presented in Appendix V. The proposed system will produce more consistent and reproducible fillings, make arbitrary profiles easier to achieve and considerably reduce the filling time.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the help and advice of Messrs P Mitchell and I McLeod during the development of the stratified facility.

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TABLE 1

Summary of Glen Fruin Stratified Tank Characteristics

Dimensions	Length	9 m
	Width	3 m
	Depth	3 m

Stratification Medium   salt (NaCl) solution

Fill Method	Present:	multilayer batch process
	Proposed:	continuous, microprocessor controlled (hardware in manufacture)

Density Profile Type   Arbitrary

Nominal range of density gradients approximately 1-9 kgm^{-4}. Significantly stronger gradients could be accommodated but implications on salt requirements and mixing would need to be considered.

Fill Rate   Recommended maximum depth increase 0.16m/hr. (maximum flowrate 1.2 l/sec).

Actual rate with present batch method depends upon the density profile required. Profiles illustrated in this report require approximately 4 working days to produce.

Rate of file with the proposed automatic process will be 0.16m/hr and be independent of the density profile. Under continuous auto-control, tank filling is expected to be achieved within a 24 hour period.

Tank Stability   The lifetime of the density profile is dependent upon usage.

The tank environment is not thermally controlled, but the sides and bottom of the tank are thermally insulated. Heat transfer through the surface generates, in time, a temperature gradient which either reinforces or reduces the magnitude of the salinity produced density gradient. This effect over a 3 month period is presented in the text.

FIG. 1 TANK ENVIRONMENT

FIG. 2 TANK PRIOR TO CONVERSION

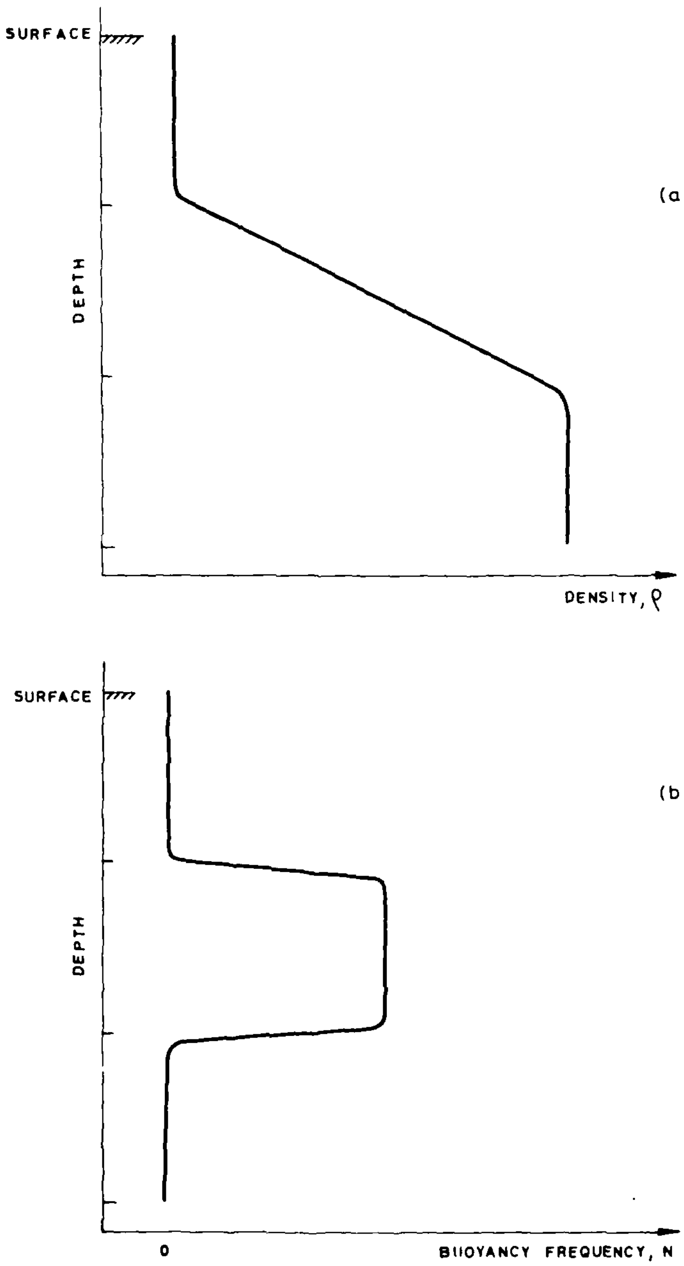


FIG. 3 DENSITY AND BUOYANCY FREQUENCY PROFILES

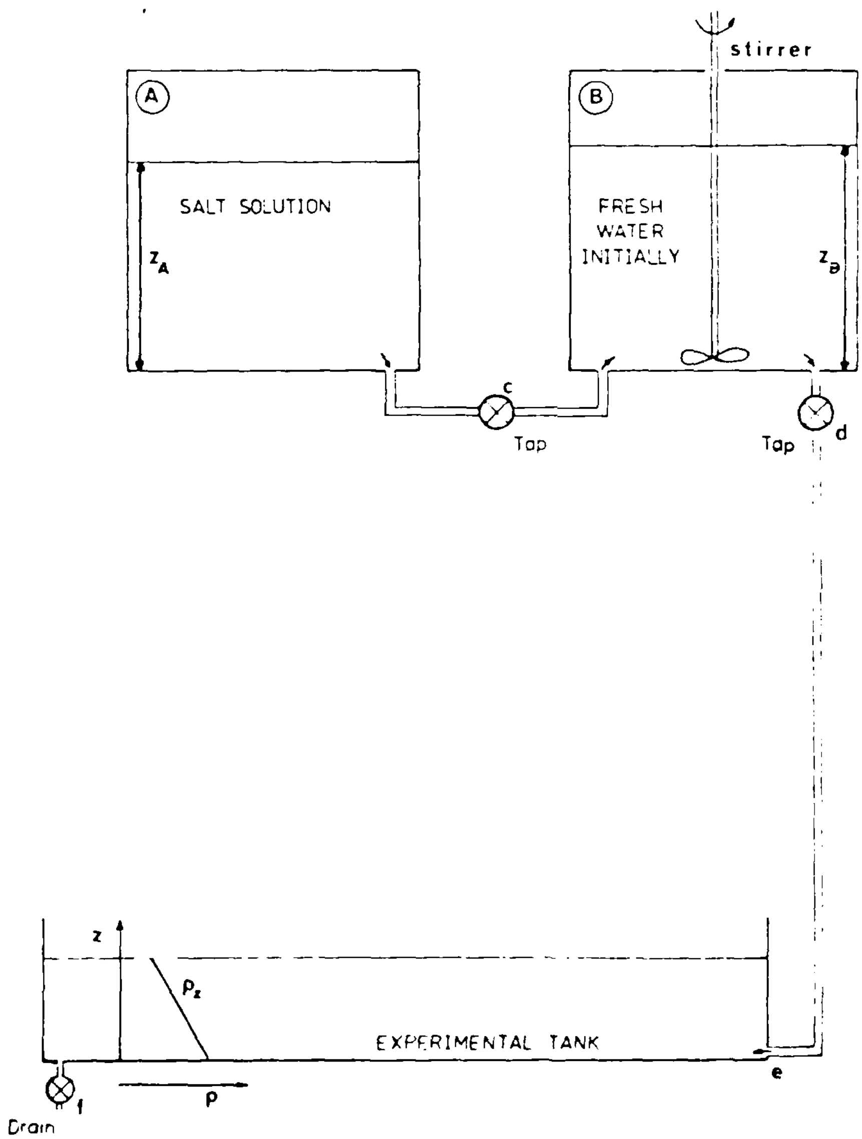


FIG. 4 SCHEMATIC DIAGRAM OF 'TWO-BIN' FILLING METHOD

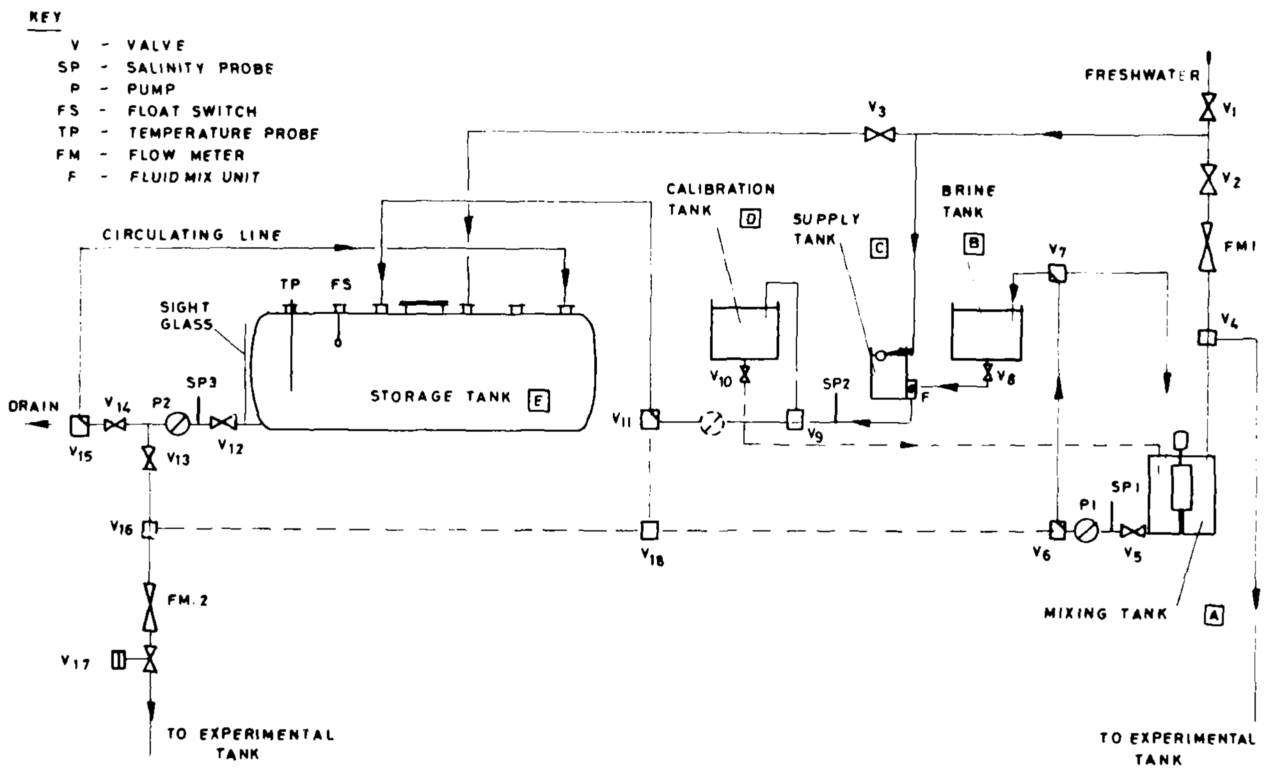


FIG 5 ORIGINAL TANK FILLING SYSTEM

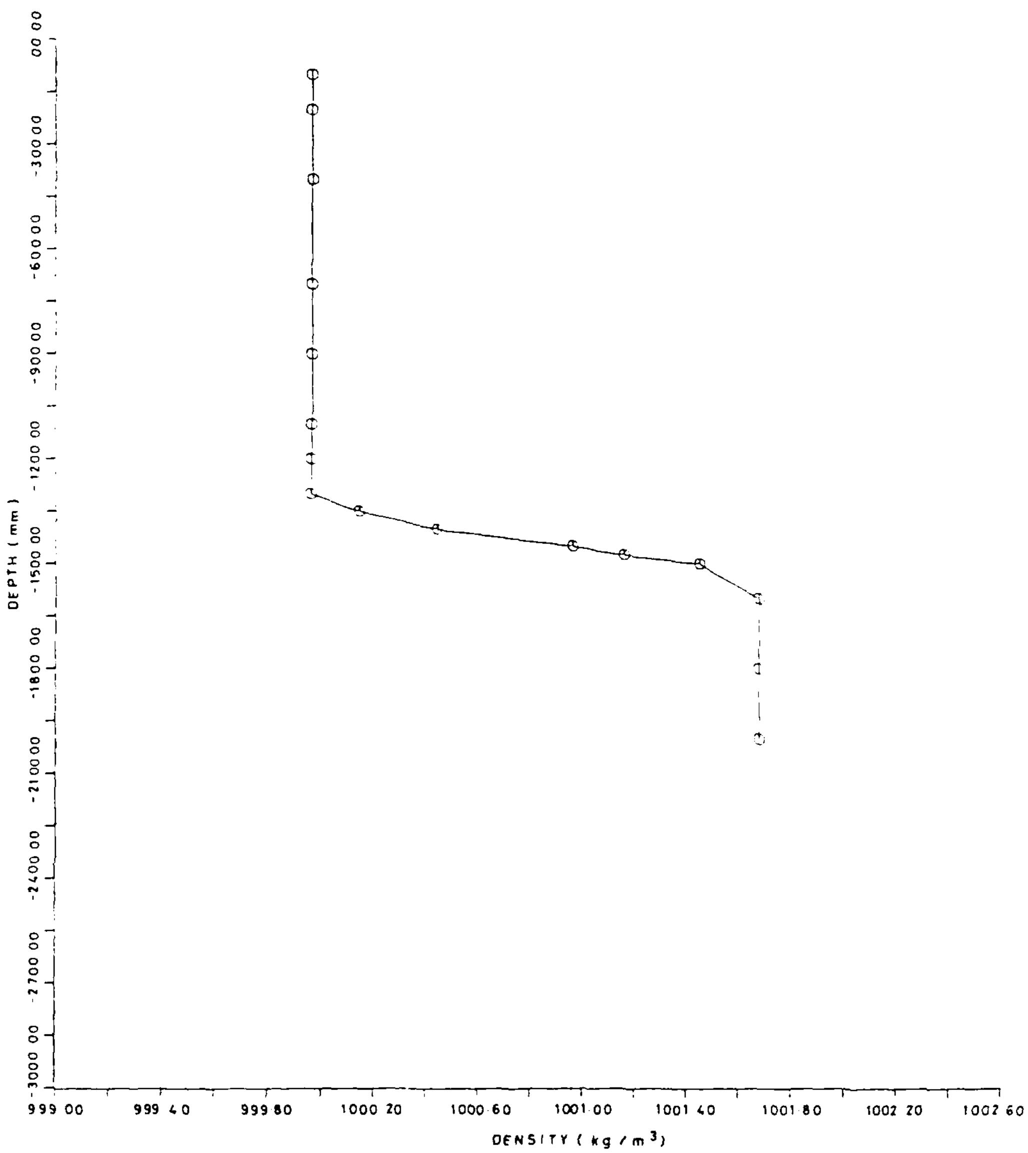


FIG. 6 FIRST FILL DENSITY PROFILE 21 DEC 1981

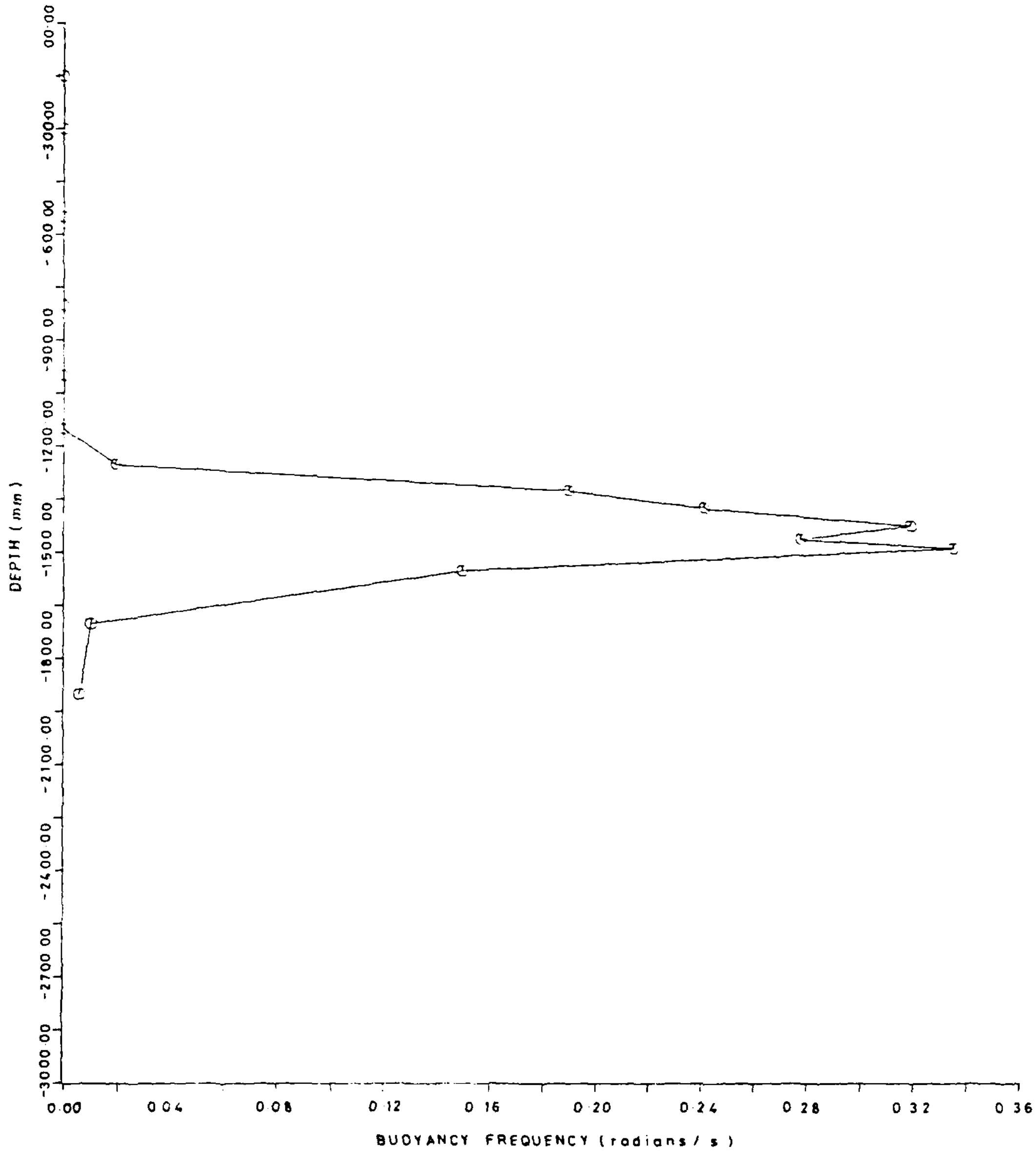


FIG. 7 FIRST FILL BUOYANCY PROFILE 21 DEC 1981

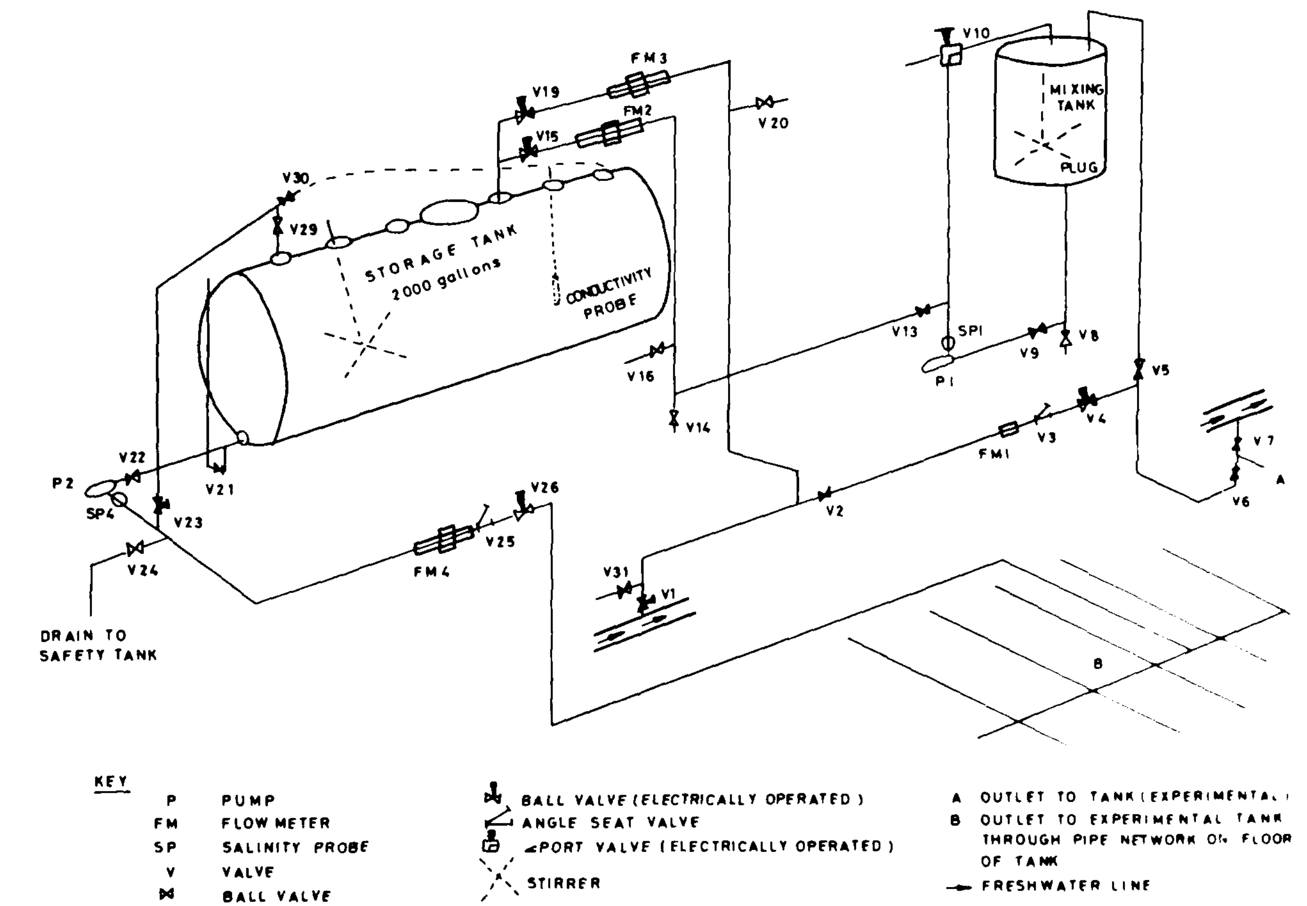


FIG. 8 MODIFIED TANK FILLING ARRANGEMENT

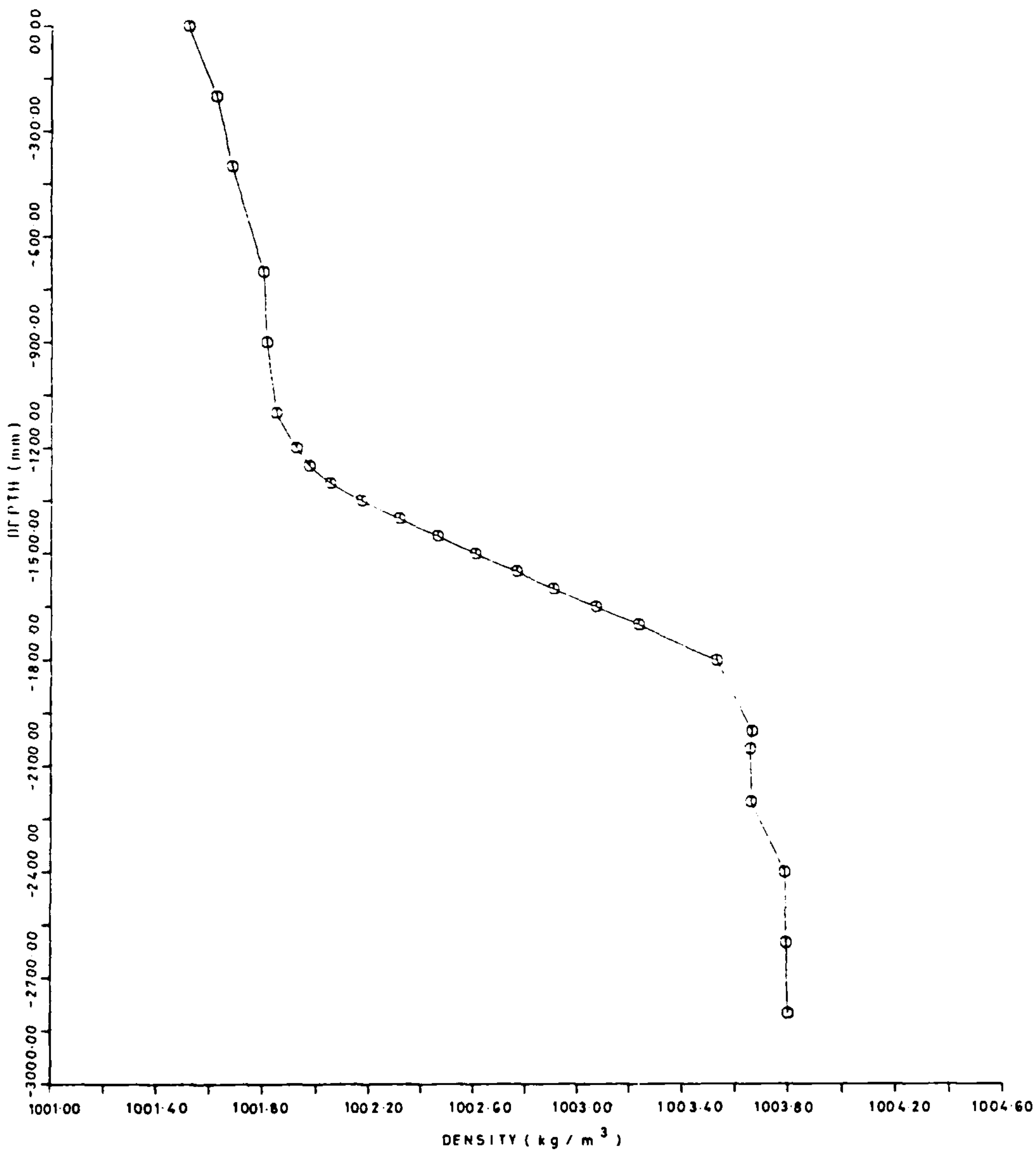


FIG. 9 EARLY DENSITY PROFILE WITH
MODIFIED FILLING SYSTEM 12 JULY 1982

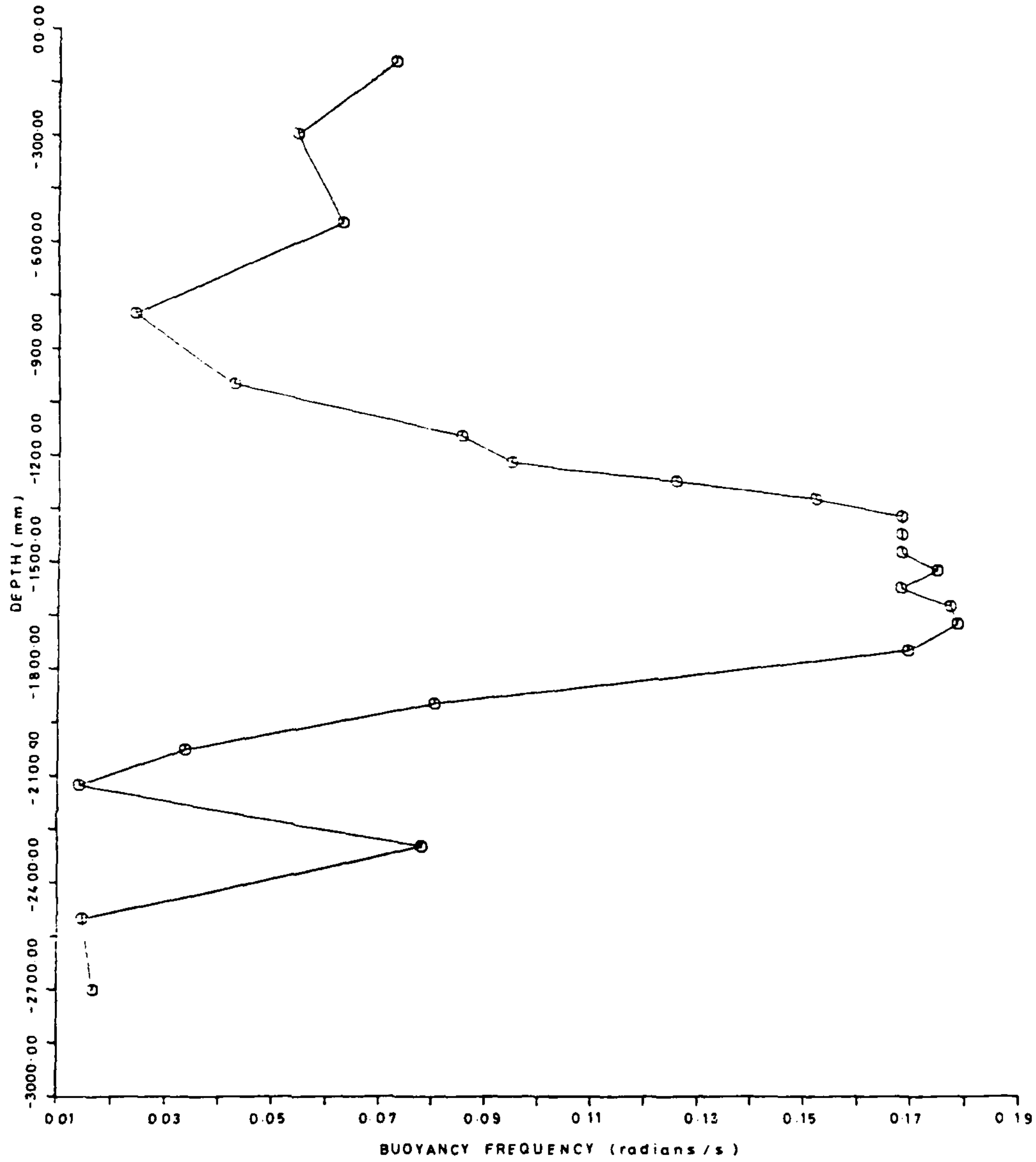


FIG.10 EARLY BUOYANCY PROFILE WITH MODIFIED FILLING SYSTEM 12 JULY 1982

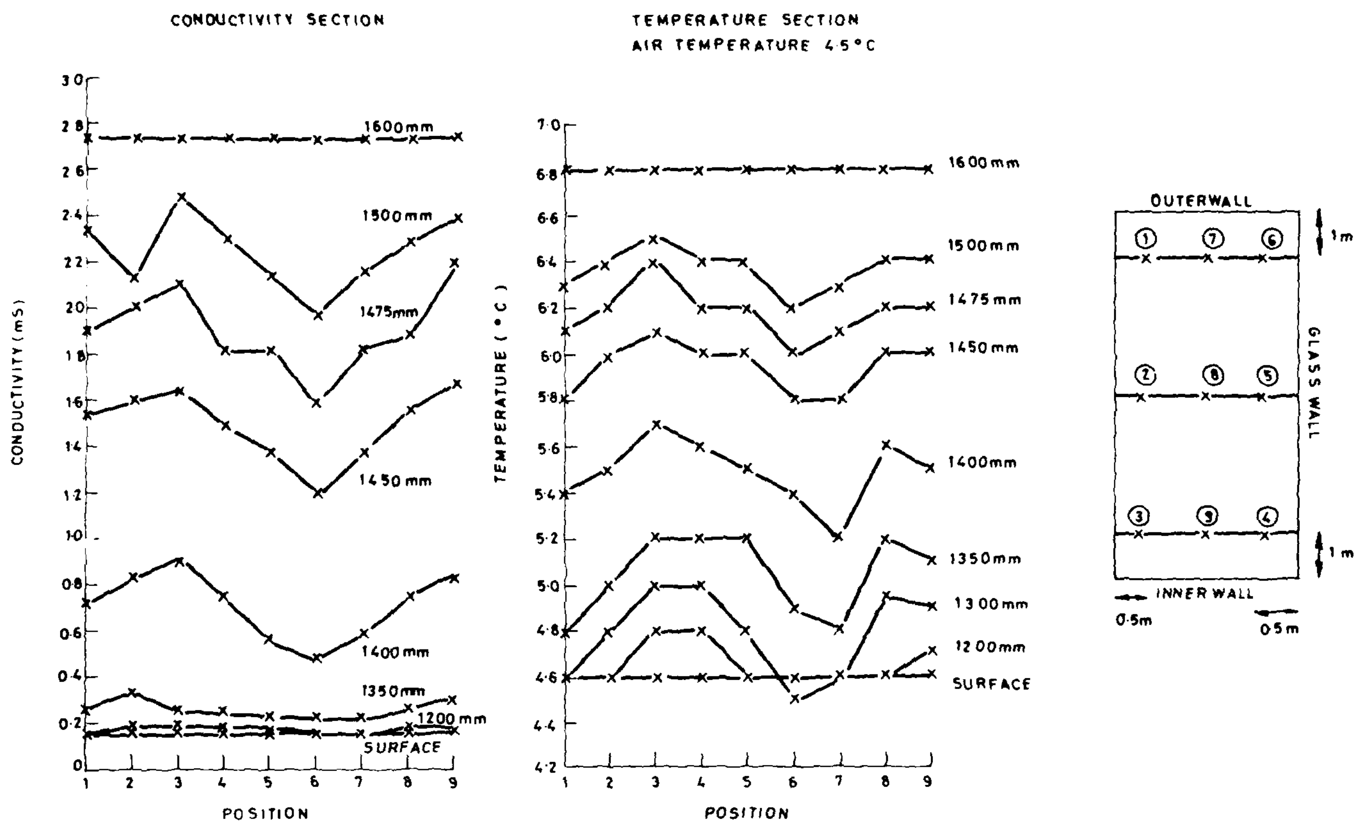


FIG. 11 TANK CONDUCTIVITY AND TEMPERATE SECTIONS 21 DEC 1981

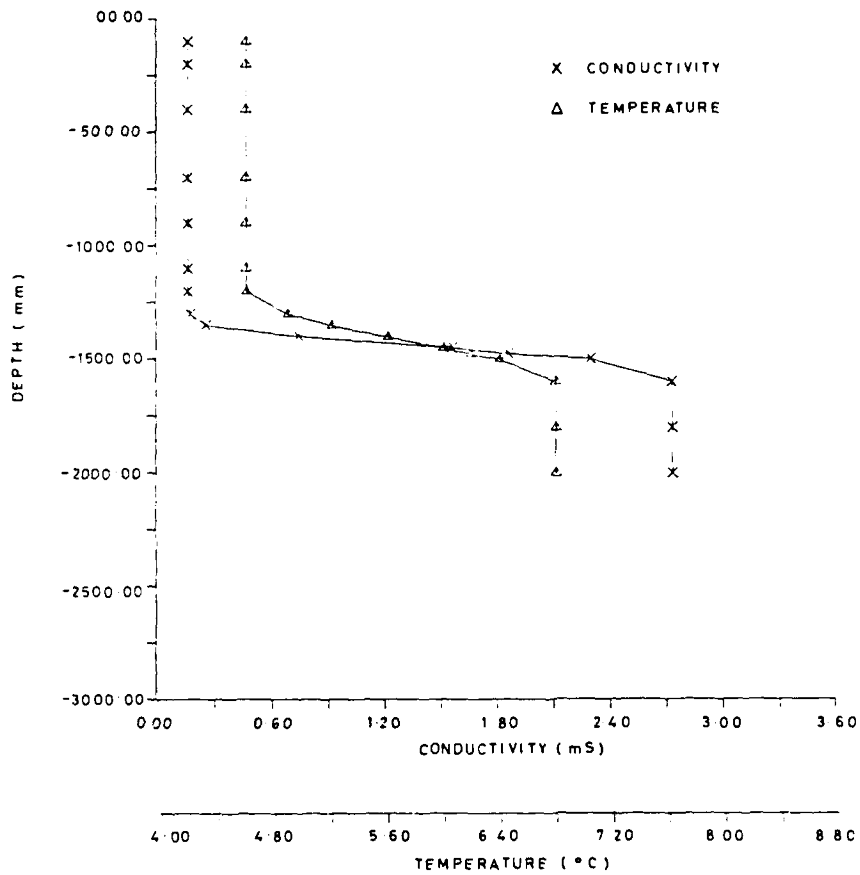


FIG. 12 CENTRE TANK TEMPERATURE
AND CONDUCTIVITY PROFILES 21 DEC 1981

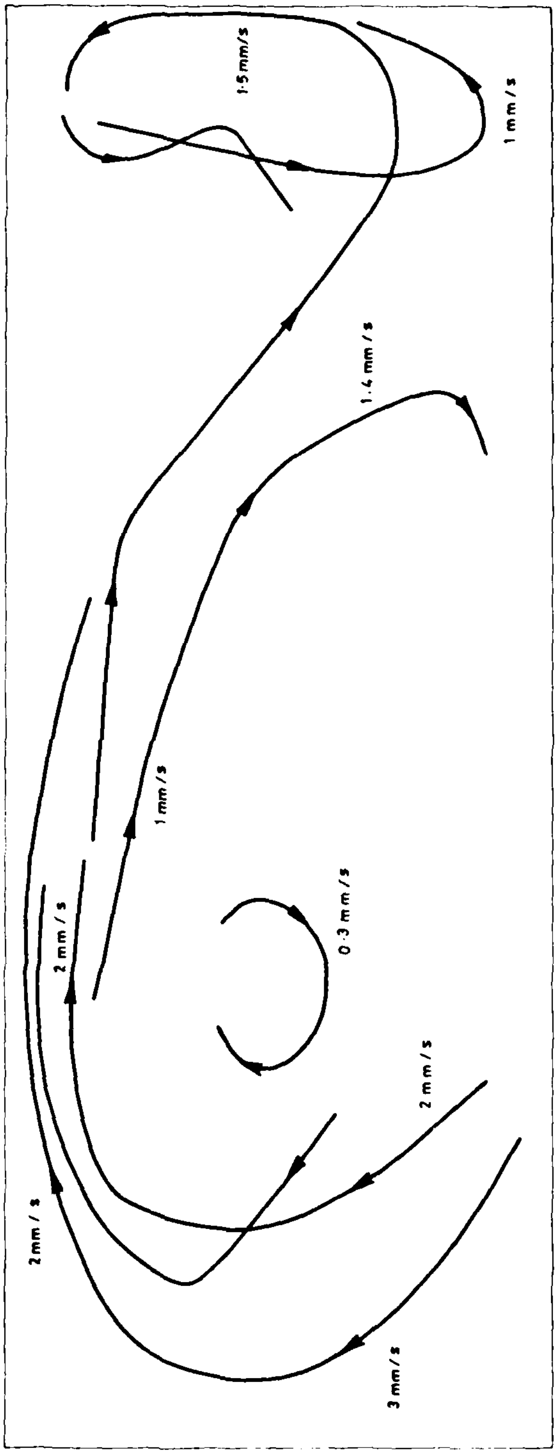


FIG. 13 SURFACE FLOAT MIGRATION PATTERNS

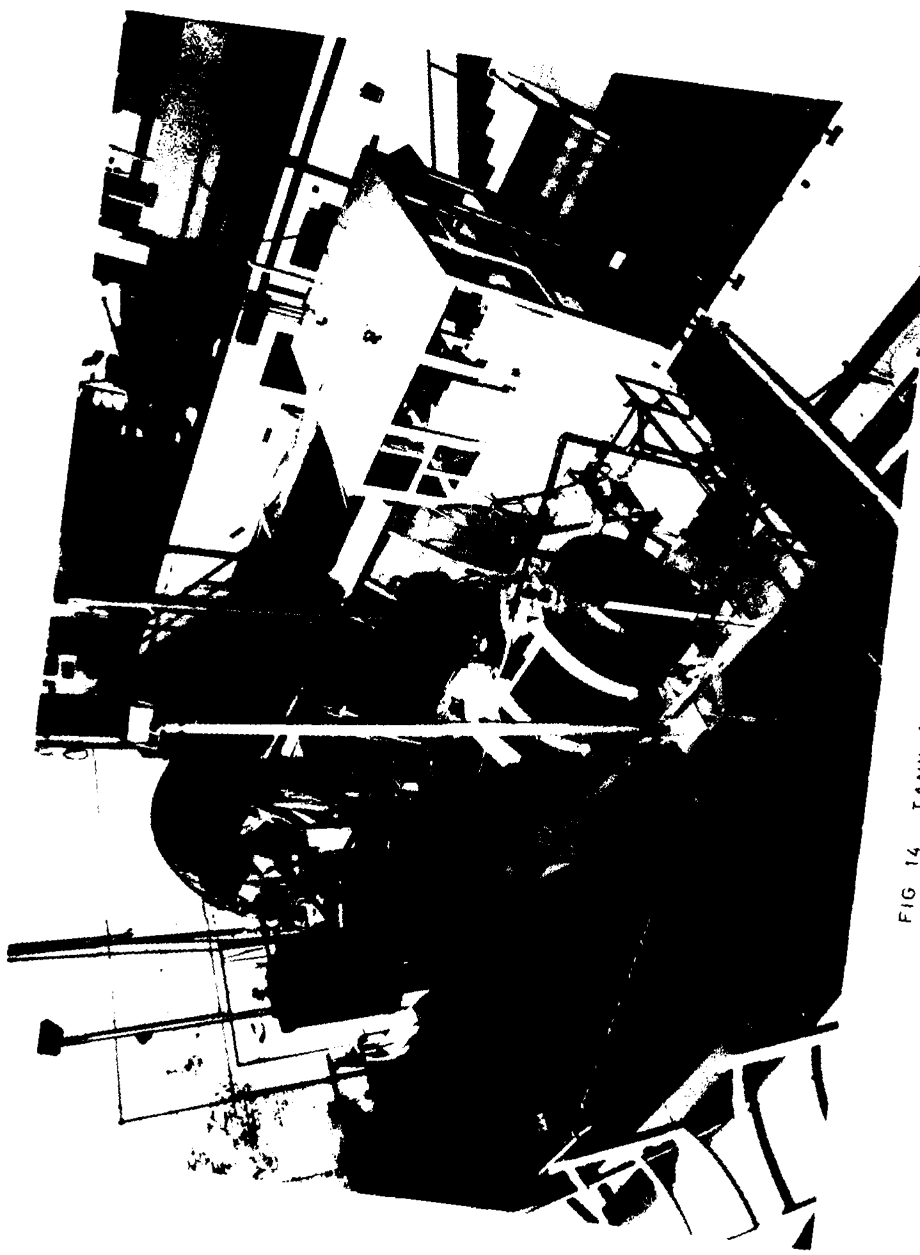


FIG 14 TANK 'GREENHOUSE' COVER

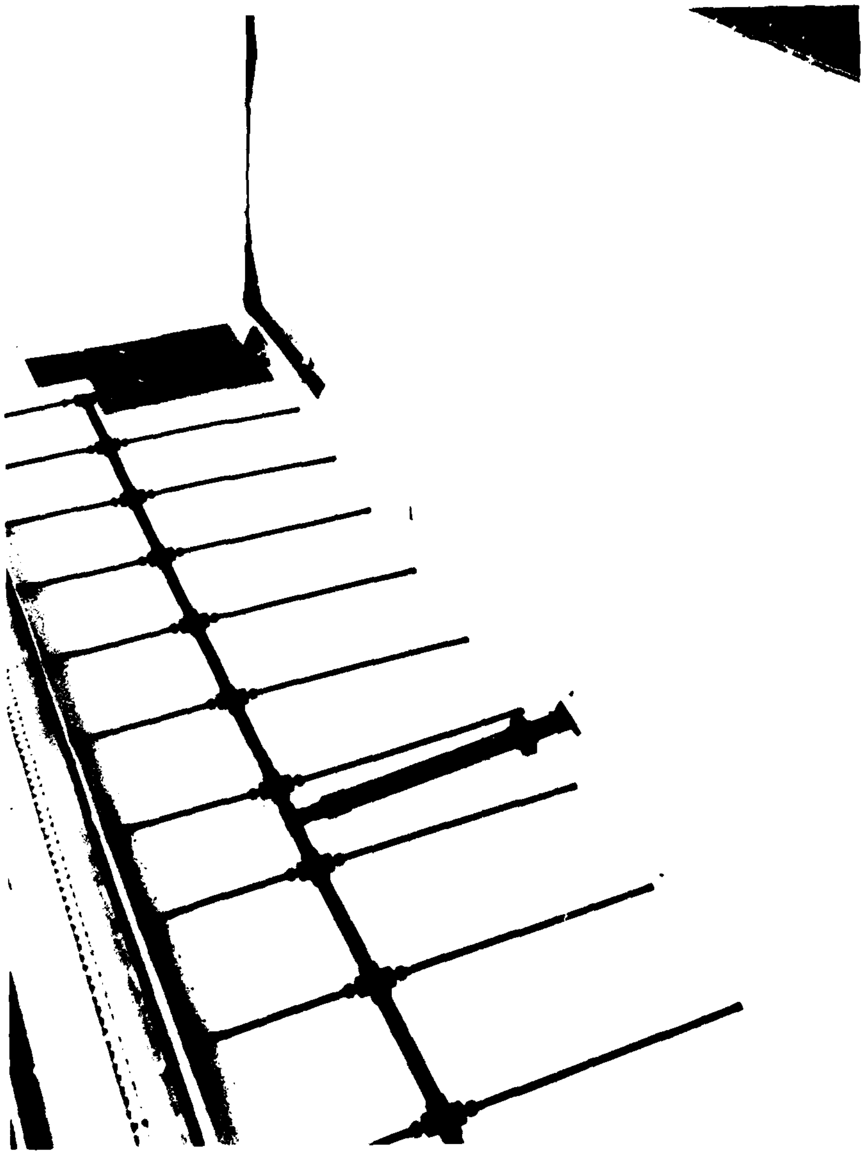


FIG 15 INTERIOR OF TANK AFTER INSULATION

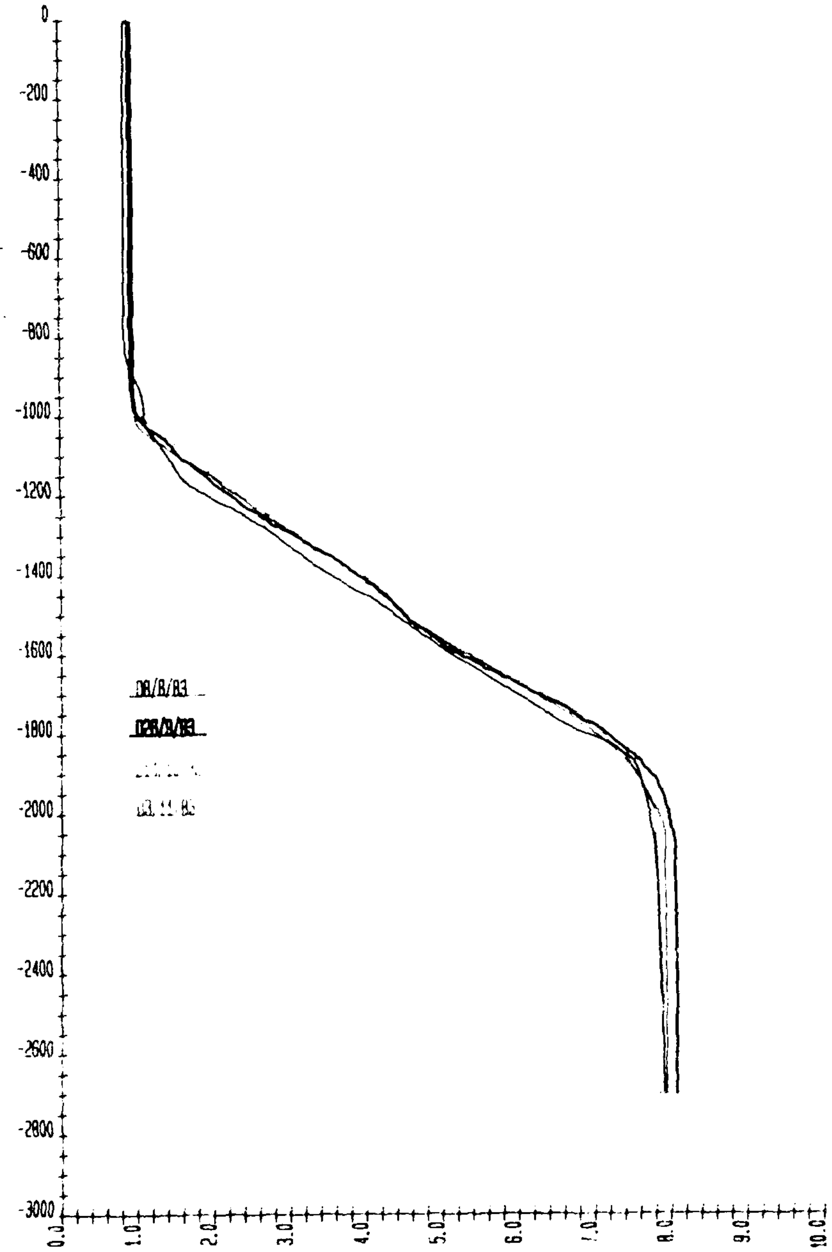


FIG 16 3 MONTH VARIATION IN SALINITY PROFILE

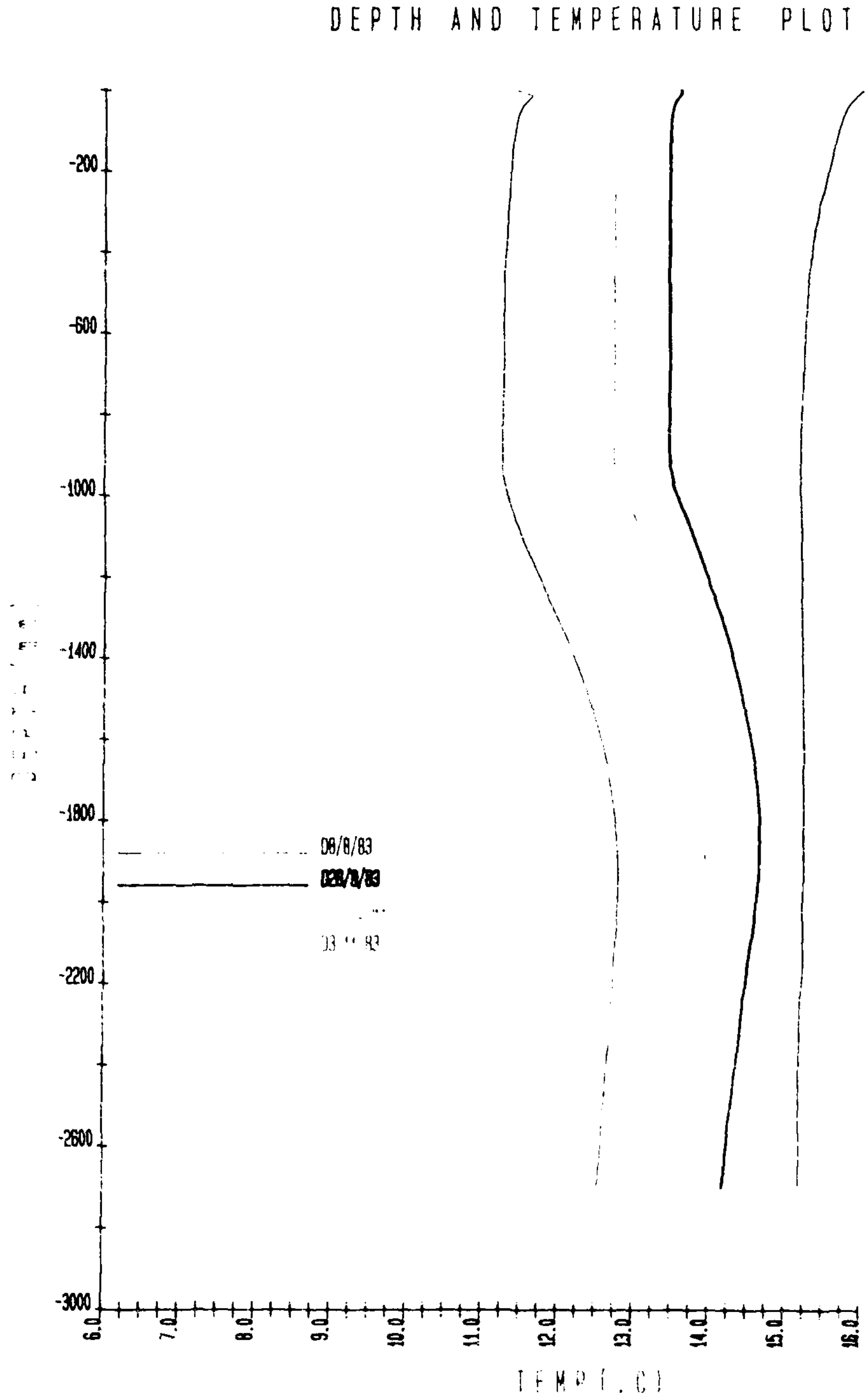


FIG 17 3 MONTH VARIATION IN TEMPERATURE PROFILE

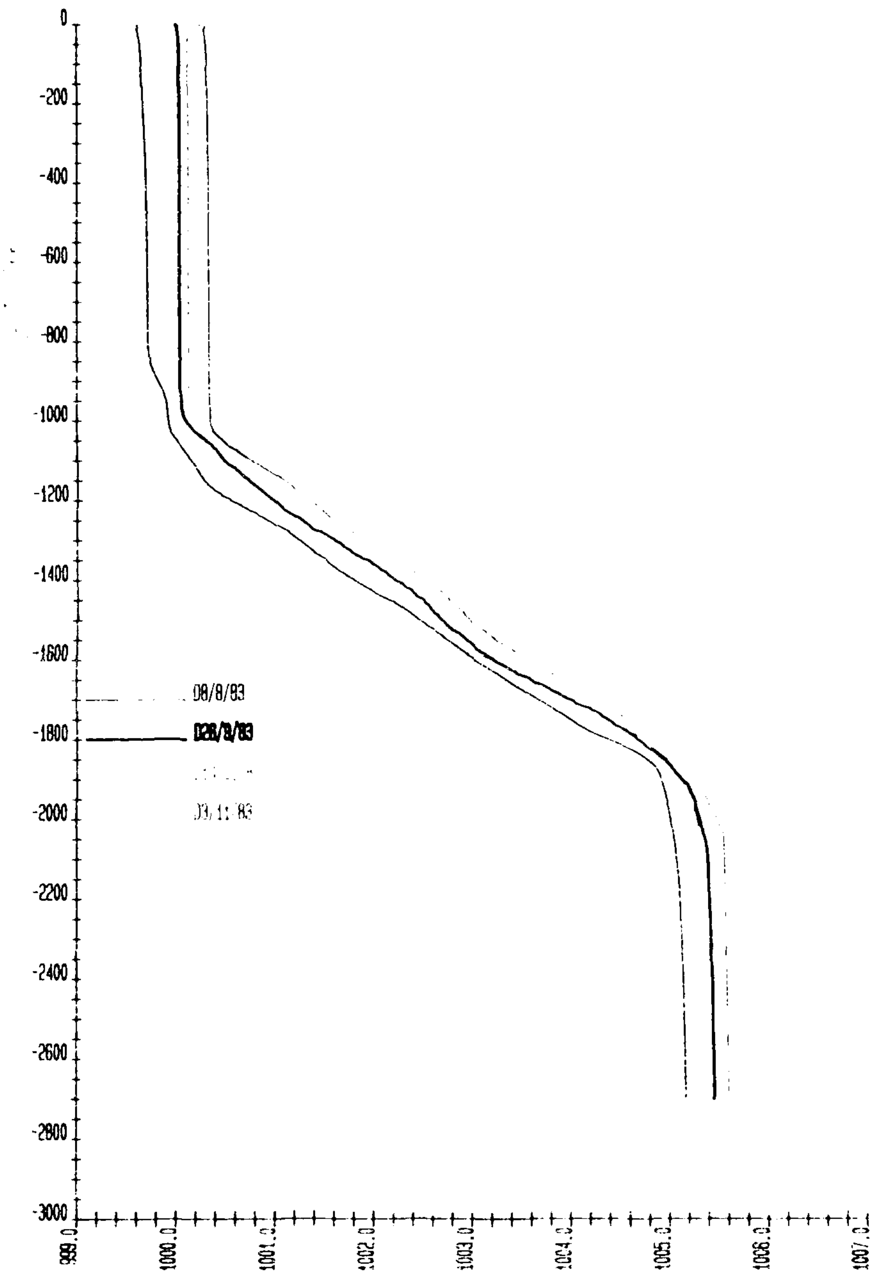


FIG 18 3 MONTH VARIATION IN DENSITY PROFILE

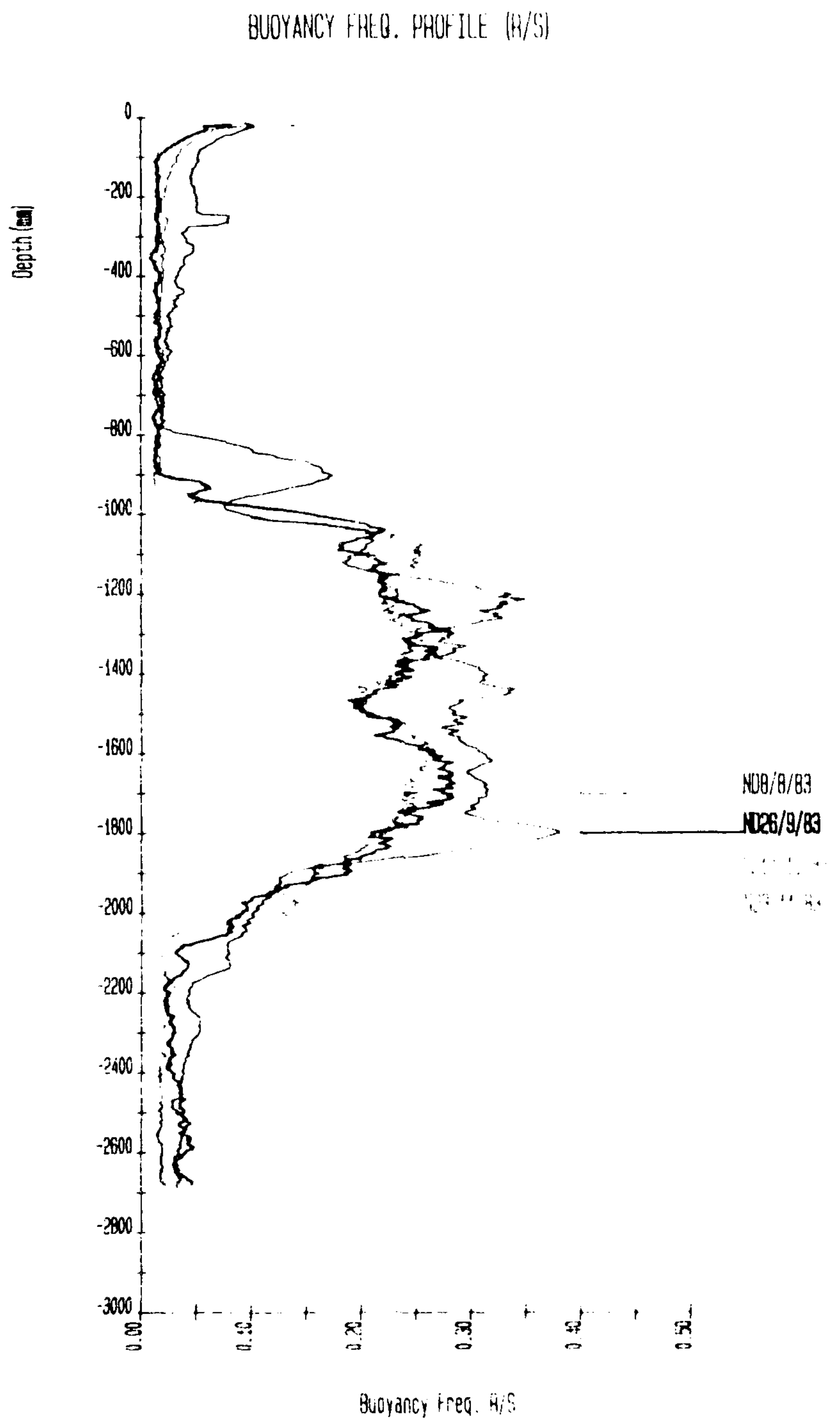


FIG 19 3 MONTH VARIATION IN BUOYANCY FREQUENCY PROFILE

APPENDIX I

The 'Two-Bin' Stratifying Method

Figure 4 is a sketch of the 'two-bin' method of producing a linear density gradient developed Oster and Yamamoto. The basic method is outlined below.

With drain taps c, d and f closed, tank A is filled to a depth z_A with salt solution of slightly higher density ρ_A than that required at the bottom of the experimental tank. The volume is equal to half the capacity of the experimental tank. Tank B is fitted with fresh water to a depth Z_B such that $\rho_B z_B = \rho_A z_A$, thereby ensuring equal hydrostatic pressure at either side of tap C.

The stirrer in tank B is located as close as possible to the inlet and outlet to ensure efficient mixing. Tap C is opened and the stirrer operates. Tap d is opened to obtain the required filling rate, the flow driven by pump or by gravity.

Taps c and d and the stirrer are turned off when the experimental tank is full. The resultant density gradient is linear with fresh water at the surface and a density at the bottom slightly lower than that of the original solution in tank A, since some solution will be left in the tanks.

APPENDIX II

Unsteady Interphase Mass Transfer

Consider the mass transfer of substance A between two static semi-infinite layers, 1 and 2, in which the concentration of substance A is C_{A1} and C_{A2} respectively as shown in Figure AII-1. The concentration of A is assumed to be small so that Ficks law may be used in both layers.

The governing equations for the diffusion are

$$\frac{\partial C_{A1}}{\partial t} = -D_1 \frac{\partial^2 C_{A1}}{\partial z^2}, \qquad 0 < z < +\infty$$

$$\frac{\partial C_{A2}}{\partial t} = -D_2 \frac{\partial^2 C_{A2}}{\partial z^2}, \qquad -\infty < z < 0$$

where z is the vertical direction, t is time and where D_1 and D_2 are the diffusion coefficients in the corresponding layers.

The above equations show that for regions where there is a linear gradient, ie dC_A/dz = constant, so that $\partial^2 C_A/\partial z^2 = 0$, the gradient is locally steady. Changes only occur in nonlinear gradients which must propagate from the boundaries of the linear regions.

The initial and boundary conditions are:

$$t = 0, \qquad C_{A1} = C_{A10}, \quad \text{for} \quad 0 < z < +\infty$$

$$C_{A2} = C_{A20}, \quad \text{for} \quad -\infty < z < 0;$$

$$z = 0, \qquad C_{A1} = mC_{A2},$$

$$D_1 \frac{\partial C_{A1}}{\partial z} = D_2 \frac{\partial C_{A2}}{\partial z}, \qquad \text{for all } t > 0;$$

$$Z = +\infty, \qquad C_{A1} = C_{A10},$$

$$Z = -\infty, \qquad C_{A2} = C_{A20}, \qquad \text{for all } t > 0.$$

The first boundary condition at z = 0 is the general statement of equilibrium at the interface where m is the distribution coefficient or Henry's law constant. The other boundary condition at z = 0 equates the molar flux in each layer across the interface.

Solving the above set of equations and boundary conditions by Laplace transforms gives the following concentration profiles:

$$\frac{C_{A1} - C_{A10}}{C_{A2} - mC_{A10}} = \frac{1 + \operatorname{erf}(Z/\sqrt{(4D_1 t)})}{m + \sqrt{(D_1/D_2)}}$$

$$\frac{C_{A2} - C_{A20}}{C_{A10} - (1/m)C_{A20}} = \frac{1 - \operatorname{erf}(Z/\sqrt{(4D_2 t)})}{(1/m) + \sqrt{(D_2/D_1)}} \quad .$$

In this particular case the Henry's law constant, m, is unity and for all practical purposes $D_1 = D_2 = D$, so that the general solution can be simplified to:

$$\frac{C_{A1} - C_{A10}}{C_{A20} - C_{A10}} = \frac{1 + \operatorname{erf}(Z/\sqrt{(4Dt)})}{2} \, ,$$

$$\frac{C_{A2} - C_{A20}}{C_{A10} - C_{A20}} = \frac{1 - \operatorname{erf}(Z\sqrt{(4Dt)})}{2} \, ,$$

i.e. the diffusion profile is non-dimensionalised.

Assuming that the temperature is constant throughout, for weak saline solutions changes in density are proportional to changes in salinity

$$\Delta\rho \propto \Delta s \quad .$$

For saline solutions at 15°C, D is 1.15 $\times 10^{-5}$ cm^2/s. Figure AII-2 shows the diffusion produced concentration profiles (non-dimensionalised with respect to the initial layer values) at times following the production of a sharp interface at time zero.

Superimposed is a typical experimental density (concentration) profile. It is seen that diffusion processes alone would take between 5 x 10^7 and 10^8 seconds (ie 18 months to 3 years) to generate an approximation to the experimental profile.

The non-dimensionalised profile also shows that the relative behaviour with time is independent of the values of C_{A10} and C_{A20}. The depth of the interface region is the prime factor so that the greater the depth extent of the experimental gradient, or equivalently the weaker the concentration gradient for any preset boundary conditions, the more stable in terms of diffusion it becomes. In this context larger facilities suffer less profile variation than smaller tanks. [Note that the molar flux through the interface is given by $D\partial C_A/\partial z$ or $D(\Delta C/\Delta z)$].

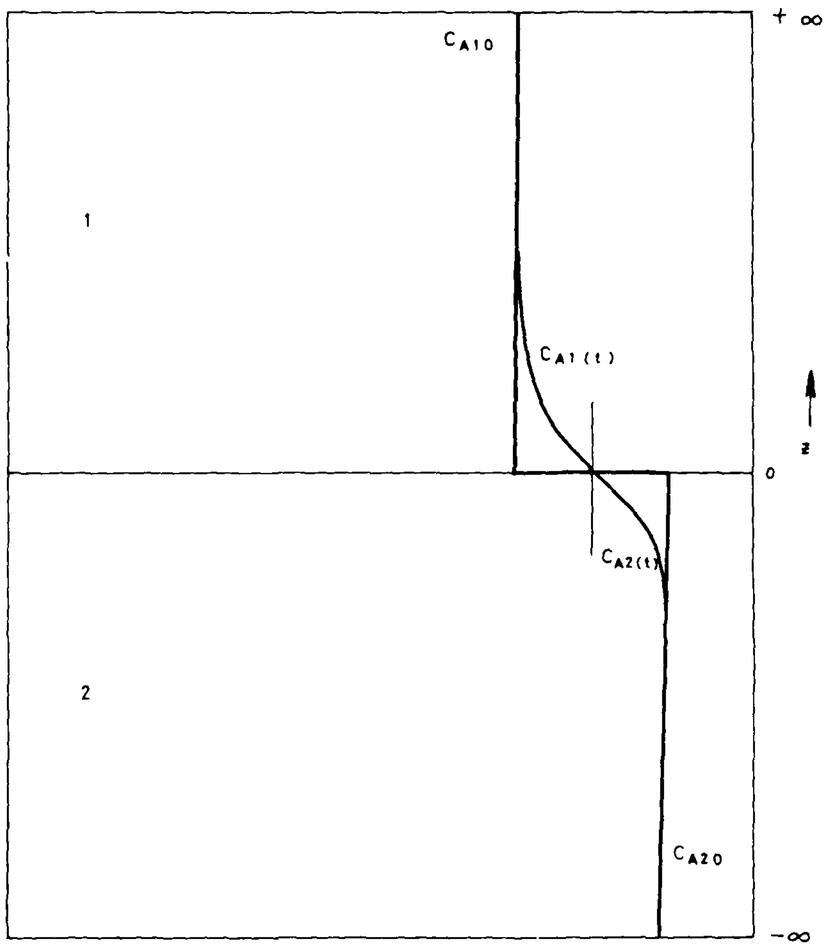


FIG. AII - 1 DEFINITION SKETCH

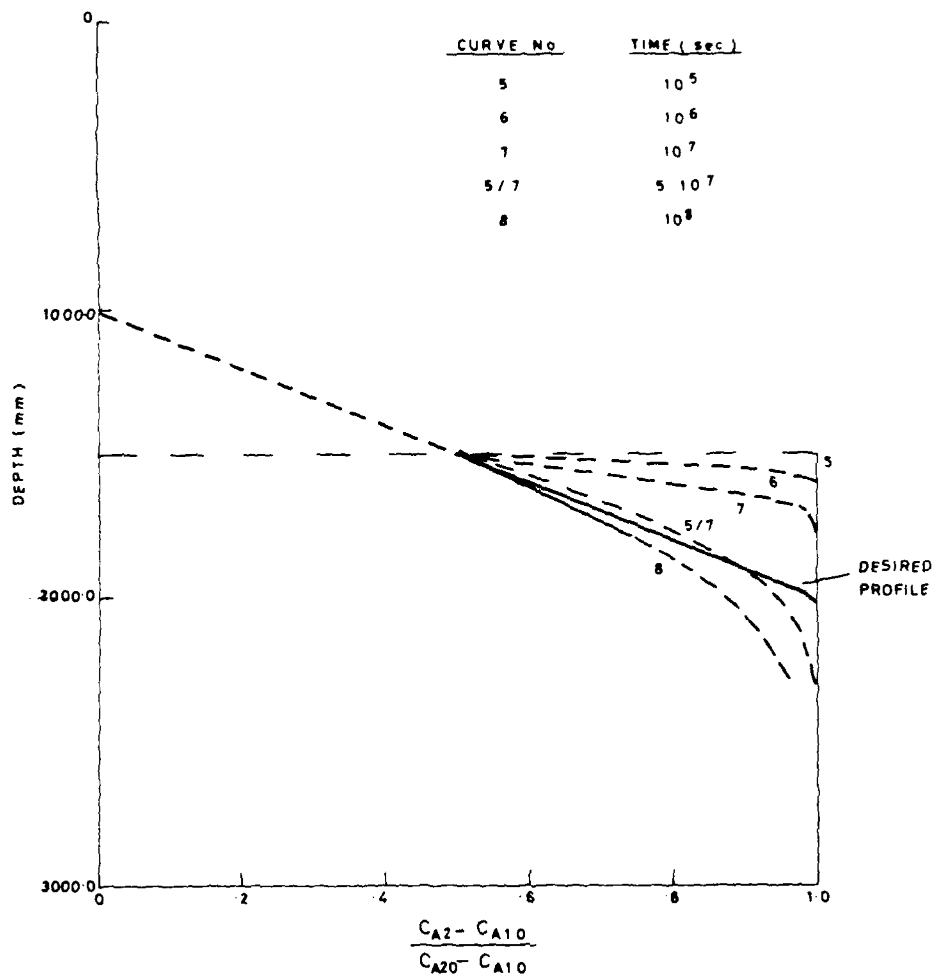


FIG. AII - 2 GROWTH OF THE INTERFACE REGION THROUGH DIFFUSION COMPARED TO REQUIREMENTS FOR THE GLEN FRUIN TANK

APPENDIX III

INITIAL SMALL SCALE EXPERIMENTS

The object of these experiments, carried out in a small glass tank, 1.829 x 0.609m x 0.609m, situated in a nominally constant temperature laboratory, was to determine the method and constraints in producing a stable weak density gradient in a larger tank, 9m x 3m x 3m.

The density gradients were generated by introducing fluid layers of increasing density through a diffuser at the bottom of the glass tank and allowing molecular diffusion overnight to smooth the profile. The inlet diffuser consisted of a 1.27cm diameter plastic tube with 30 holes of 0.158cm diameter at 5.08cm spacing along its length. The hole size and spacing were kept constant and two different diffusers were tested - one with a single hole pointing towards the bottom of the tank and one with two outlet holes drilled along a diameter and positioned to give a horizontal outflow.

The rate at which salt solution was introduced into the tank was slow in order to avoid excessive mixing. This was judged visually by making use of the variations in refractive index of the solution. Also, measurements of the interfacial layer thickness wre made using a conductivity probe (Tacussel type CM08 22G coupled with a Tacussel meter type CD78). The filling tests were repeated using different flowrates and with an overall change of specific gravity, between the top and bottom of the tank varying between .015 and .001. The specific gravity was determined with a specific gravity hydrometer, range 1.00 - 1.025, accuracy .005. For monitoring changes in very weak salt solutions the conductivity method was much more sensitive. A plot of conductivity of Na Cl solution at $20^{\circ}C$ against relative density (ie density of pure water at $4^{\circ}C$ defined to be unity (cgs system) so that relative density is equivalent to specific gravity) is shown in Figure AIII - 1.

As expected, the inlet diffuser with the two horizontal holes was found to produce a better inflow than the single vertical hole. With this diffuser, a flow rate of 178 l/hr, corresponding to a rate of depth increase of 0.16 m/hr, was found to represent a reasonable compromise between fill time and the prevention of mixing.

The number of layers required for the large tank was determined by the growth rate of the interface between adjacent layers. Initially after filling, the interface thickness, determined by conductivity measurements, was typically 7cm which increased to about 10cm after 2 days. A comparison of the theoretical and measured diffusion profiles obtained 1 week and 1 month after initial fill for a lower layer specific gravity of 1.006 (top layer fresh water) is shown in figure AIII-2. The theoretical diffusion profile is presented in Appendix II.

It was therefore decided, on the basis of these tests, that the nominal layer depth for use in stratifying the large tank would be 10cm. The maximum rate of depth increase would be limited to 0.16cm/hr and the total length of the diffuser scaled according to plan area.

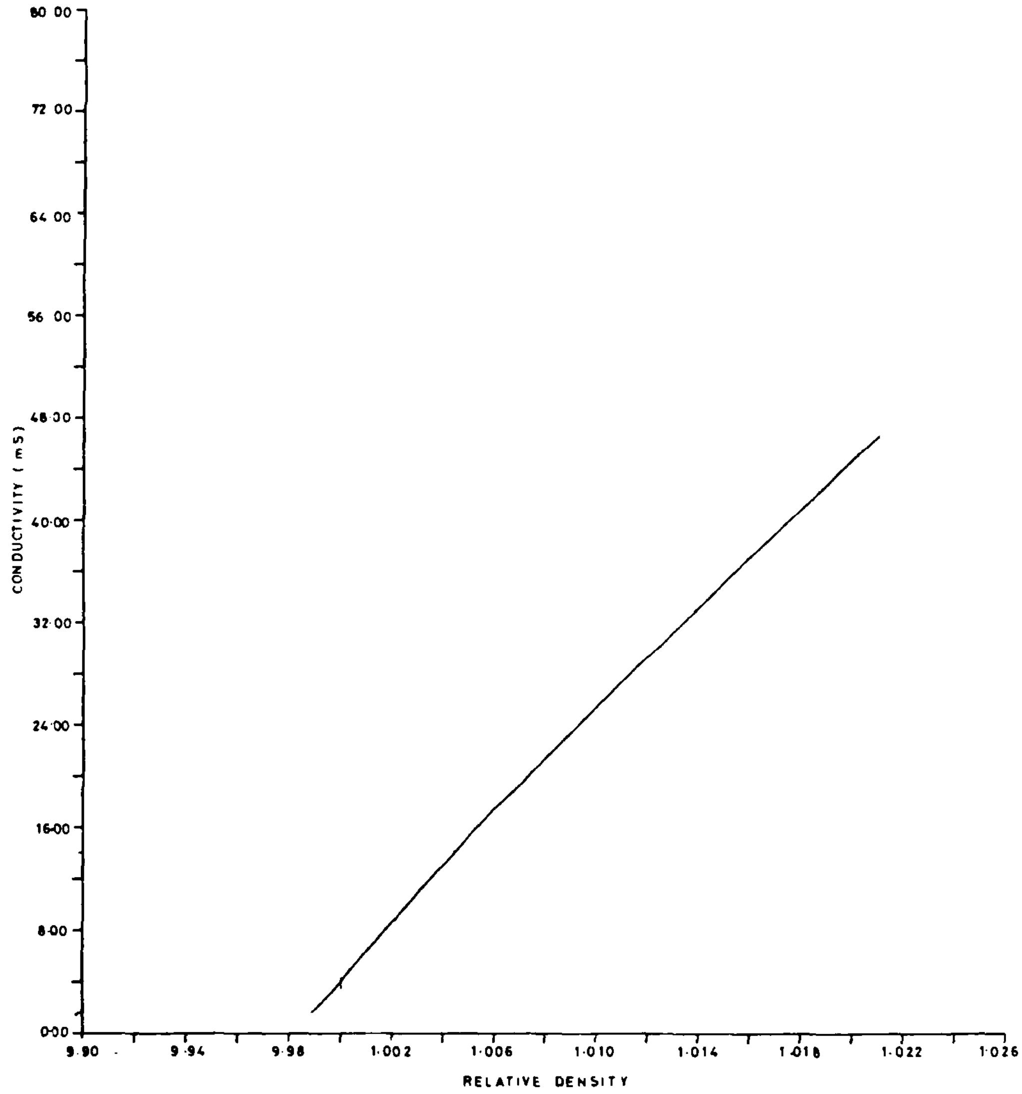
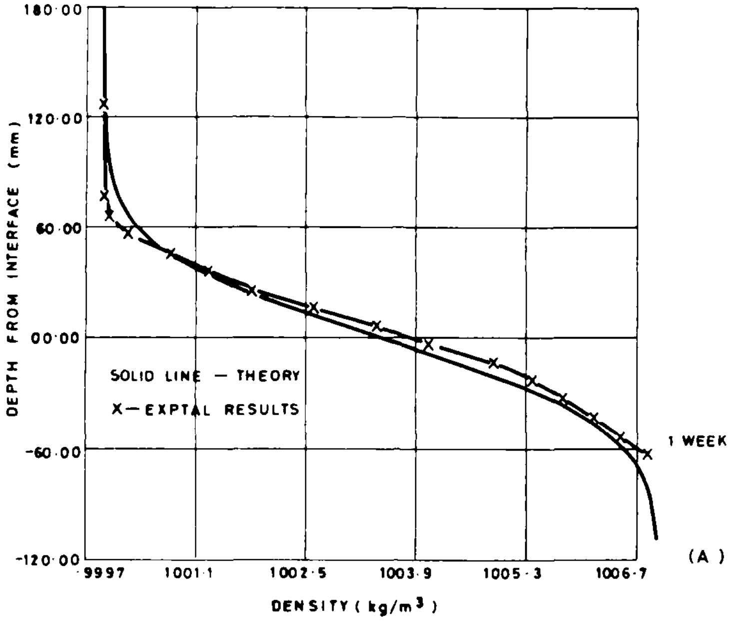
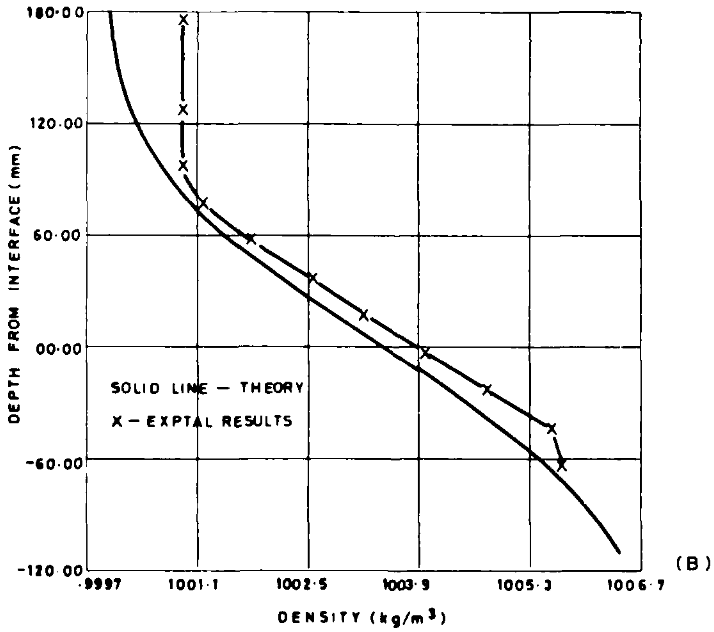


FIG AIII - 1 CONDUCTIVITY - RELATIVE DENSITY CHARACTERISTICS FOR NaCl SOLUTION AT 20°C



(A)



(B)

FIG. AIII-2 DIFFUSION PROFILE COMPARISON OF THEORY AND EXPERIMENT (A) 1 WEEK (B) 1 MONTH

APPENDIX IV

INTERNAL WAVE DISPERSION CHARACTERISTICS FOR A TYPICAL TANK PROFILE

Internal wave propagation characteristics (ie wavenumber, phase and group velocity) are related by a wave dispersion equation which in turn is dependent upon the type and detail of the density profile. Unlike the simple case of surface waves, where only one propagation mode exists, internal wave motion, because of its three dimensional anisotopric nature, is experienced by the bulk of the fluid and can propagate via many different vertical modes.

In order to gain a semi-quantitative appreciation of the internal wave propagation characteristics for the Glen Fruin tank the dispersion equation was solved using a routine based on one developed by Milder (24)*.

For simplicity, the tank buoyancy profile was approximated as three separate regions with the following values: (a buoyancy frequency of 0.14 rad/s was chosen as typical of a weak gradient)

Depth	0 - 0.9m	$N = 0$
	0.9 - 1.9m	$N = 0.14$ rad/s
	1.9 - 3.0m	$N = 0$

(Slight variations in the depth location of the gradient region are not considered to be significant in terms of the approximations made).

Figures A-IV - 1 and 2*, show plots of the frequency - wavenumber dispersion relationship for the lowest 20 modes. A printout displaying frequency, wavenumber, phase and group velocity for the lowest 10 modes is given in Table AIV-1. The internal wave phase velocity is related to wavenumber (k) and frequency (ω) through ω/k and the group velocity is given by $d\omega/dk$.

Larger values of buoyancy frequency in the gradient region generally lead to higher propagation velocities. The approximation of the profile as three distinct layers, with the corresponding discontinuity in the buoyancy profile, is expected to be reasonable for the low vertical mode numbers but less so, although still of correct order, for the higher mode numbers (corresponding to the smaller vertical scales over which the real profile shows more significant difference from the approximation).

---

* K Dumper, Plessey Electronic Systems Research Ltd. Report 17/83/R092C (1983).

Table A-IV - 1

Wave Dispersion Date for the First 10 modes

Buoyancy Frequency = 0.14 rad/s
Depth to top of density gradient region = 0.9m
Depth to bottom of density gradient region = 1.9m
Overall depth

Mode number 1

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	1.038E-03	1.038E-01	1.038E-01
2.000E-02	2.075E-03	1.038E-01	1.037E-01
5.000E-02	5.184E-03	1.037E-01	1.034E-01
1.000E-01	1.033E-02	1.033E-01	1.024E-01
2.000E-01	2.041E-02	1.020E-01	9.958E-02
5.000E-01	4.709E-02	9.419E-02	7.753E-02
1.000E 00	7.662E-02	7.662E-02	4.262E-02
2.000E 00	1.025E-01	5.123E-02	1.526E-02
5.000E 00	1.237E-01	2.474E-02	3.181E-03
1.000E 01	1.315E-01	1.315E-02	7.074E-04
2.000E.01	1.346E-01	6.732E-03	1.211E-04
5.000E-01	1.358E-01	2.715E-03	9.413E-06
1.000E-02	1.359E-01	1.359E-03	1.233E-06

Mode Number 2

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	3.698E-04	3.698E-02	3.698E-02
2.000E-02	7.396E-04	3.698E-02	3.698E-02
5.000E-02	1.849E-03	3.698E-02	3.696E-02
1.000E-01	3.695E-03	3.695E-02	3.690E-02
2.000E-01	7.374E-03	3.687E-02	3.664E-02
5.000E-01	1.815E-02	3.630E-02	3.496E-02
1.000E-00	3.453E-02	3.453E-02	3.024E-02
2.000E.00	5.981E-02	2.991E-02	2.067E-02
5.000E-00	9.859E-02	1.970E-02	7.692E-03
1.000E-01	1.201E-02	1.201E-02	2.260E-03
2.000E 01	1.307E-01	6.537E-03	4.477E-04
5.000E 01	1.350E-01	2.700E-03	3.692E-04
1.000E 02	1.357E-01	1.357E-03	4.971E-06

Mode number 3

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	2.065E-04	2.065E-02	2.065E-02
2.000E-02	4.129E-04	2.065E-02	2.065E-02
5.000E-02	1.032E-03	2.064E-02	2.064E-02
1.000E-01	2.064E-03	2.064E-02	2.063E-02
2.000E-01	4.125E-03	2.062E-02	2.058E-02
5.000E-01	1.026E-02	2.051E-02	2.025E-02
1.000E 00	2.015E-02	2.015E-02	1.922E-02
2.000E 00	3.801E-02	1.900E-02	1.638E-02
5.000E 00	7.569E-02	1.514E-02	9.254E-03
1.000E 01	1.059E-01	1.059E-02	3.690E-03
2.000E 01	1.249E-01	6.246E-03	8.903E-04
5.000E 01	1 338E-01	2.676E-03	8.092E-05
1.000E 02	1.354E-01	1.354E-03	1.109E-05

Mode Number 4

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	1.412E-04	1.412E-02	1.412E-02
2.000E-02	2.823E-04	1.412E-02	1.412E-02
5.00E-02	7.058E-04	1.412E-02	1.412E-02
1.000E-01	1.412E-03	1.412E-02	1.411E-02
2.000E-01	2.822E-03	1.411E-02	1.410E-02
5.000E-01	7.037E-03	1.407E-02	1.399E-02
1.000E 00	1.395E-02	1.395E-02	1.364E-02
2.000E 00	2.708E-02	1.354E-02	1.256E-02
5.000E 00	5.927E-02	1.185E-02	8.897E-03
1.000E 01	9.190E-02	9.190E-03	4.545E-03
2.000E 01	1.178E-01	5.892E-03	1.351E-03
5.000E 01	1.322E-01	2.644E-03	1.389E-04
1.000E 02	1.350E-01	1.350E-03	1.954E-05

Mode number 5

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	1.069E-04	1.069E-02	1.069E-02
2.000E-02	2.138E-04	1.069E-02	1.069E-02
5.000E-02	5.344E-04	1.069E-02	1.069E-02
1.000E-01	1.069E-03	1.069E-02	1.069E-02
2.000E-01	2.137E-03	1.068E-02	1.068E-02
5.000E-01	5.334E-03	1.067E-02	1.063E-02
1.000E 00	1.062E-02	1.062E-02	1.047E-02
2.000E 00	2.086E-02	1.043E-02	9.972E-03
5.000E 00	4.790E-02	9.580E-03	7.978E-03
1.000E 01	7.973E-02	7.973E-03	4.871E-03
2.000E 01	1.102E-01	5.511E-03	1.758E-03
5.000E 01	1.302E-01	2.604E-03	2.013E-04
1.000E 02	1.344E-01	1.344E-03	3.078E-05

Mode number 6

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	8.588E-05	8.588E-03	8.588E-03
2.000E-02	1.718E-04	8.588E-03	8.588E-03
5.000E-02	4.294E-04	8.588E-03	8.588E-03
1.000E-01	8.588E-04	8.588E-03	8.587E-03
2.000E-01	1.717E-03	8.587E-03	8.584E-03
5.000E-01	4.298E-03	8.579E-03	8.559E-03
1.000E 99	8.550E-03	8.550E-03	8.477E-03
2.000E 00	1.690E-02	8.451E-03	8.206E-03
5.000E 00	3.988E-02	7.975E-03	7.037E-03
1.000E 01	6.961E-02	6.961E-03	4.862E-03
2.000E 01	1.026E-01	5.128E-03	2.075E-03
5.000E 01	1.278E-01	2.557E-03	2.840E-04
1.000E 02	1.337E-01	1.337E-03	4.273E-03

Mode number 7

Wavenumber	Frequency	Phase vel	Group vel
1.00E-02	7.174E-05	7.174E-03	7.175E-03
2.000E-02	1.435E-04	7.174E-03	7.175E-03
5.000E-02	2.587E-04	7.174E-03	7.174E-03
1.000E-01	7.274E-04	7.174E-03	7.174E-03
2.000E-01	1.435E-03	7.174E-03	7.172E-03
5.000E-01	3.584E-03	7.169E-03	7.157E-03
1.000E 00	7.152R-03	7.152E-03	7.109E-03
2.000E 00	1.419E-02	7.094E-03	6.948E-03
5.000E 00	3.402E-02	6.808E-03	6.215E-03
1.000E 01	6.135E-02	6.135E-03	4.680E-03
2.000E 01	9.521E-02	4.760E-03	2.298E-03
5.000E 01	1.252E-01	2.504E-03	3.643E-04
1.000E 02	1.329E-01	1.329E-03	5.715E-03

Mode number 8

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	6.159E-05	6.159E-03	6.159E-03
2.000E-02	1.232E-04	6.159E-03	6.159E-03
5.000E-02	3.179E-04	6.159E-03	6.159E-03
1.000E-01	6.159E-04	6.159E-03	6.158E-03
2.000E-01	1.232E-03	6.158E-03	6.157E-03
5.000E-01	3.078E-03	6.155E-03	6.148E-03
1.000E 00	6.145E-03	6.145E-03	6.117E-03
2.000E 00	2.958E-02	5.918E-03	5.538E-03
5.000E 01	1.224E-01	2.448E-03	4.456E-04
1.000E 02	1.320E-01	1.320E-03	7.322E-03

Mode number 9

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	5.394E-05	5.394E-03	5.394E-03
2.000E-02	1.079E-04	5.394E-03	5.394E-03
5.000E-02	2.697E-04	5.394E-03	5.394E-03
1.000E-01	5.394E-04	5.394E-03	5.394E-03
2.000E-01	1.079E-03	5.394E-03	5.393E-03
5.000E-01	2.696E-03	5.392E-03	5.387E-03
1.000E 00	5.385E-03	5.385E-03	5.366E-03
2.000E 00	1.072E-02	5.359E-03	5.296E-03
5.000E 00	2.615E-02	5.230E-03	4.960E-03
1.000E 01	4 903E-02	4 903E-03	4 149E-03
2.000E 01	8.207E-02	4.103E-03	5.253E-04
5.000E 01	1.194E-01	2.388E-03	5.253E-04
1.000E 02	1.311E-01	1.311E-03	9.067E-05

Mode number 10

Wavenumber	Frequency	Phase vel	Group vel
1.000E-02	4.798E-05	4.798E-03	4.798E-03
2.000E-02	9.596E-05	4.798E-03	4.798E-03
5.000E-02	2.399E-04	4.798E-03	4.798E-03
1.000E-01	4.798E-04	4.798E-03	4.798E-03
2.000E-01	9.595E-04	4.798E-03	4.797E-03
5.000E-01	2.398E-03	4.796E-03	4.793E-03
1.000E 00	4.791E-03	4.791E-03	4.778E-03
2.000E 00	9.547E-03	4.773E-03	4.729E-03
5.000E 00	2 340E-02	4.681E-03	4.487E-03
1.000E 01	4.42E-02	4.442R-03	3.878E-03
2.000E 01	7.638E-02	3.819E-03	2.522E-03
5.000E 02	1.300E-01	1.300E-03	1.092E-04
1.000E 02	1.300E-01	1.300E-03	1.092E-04

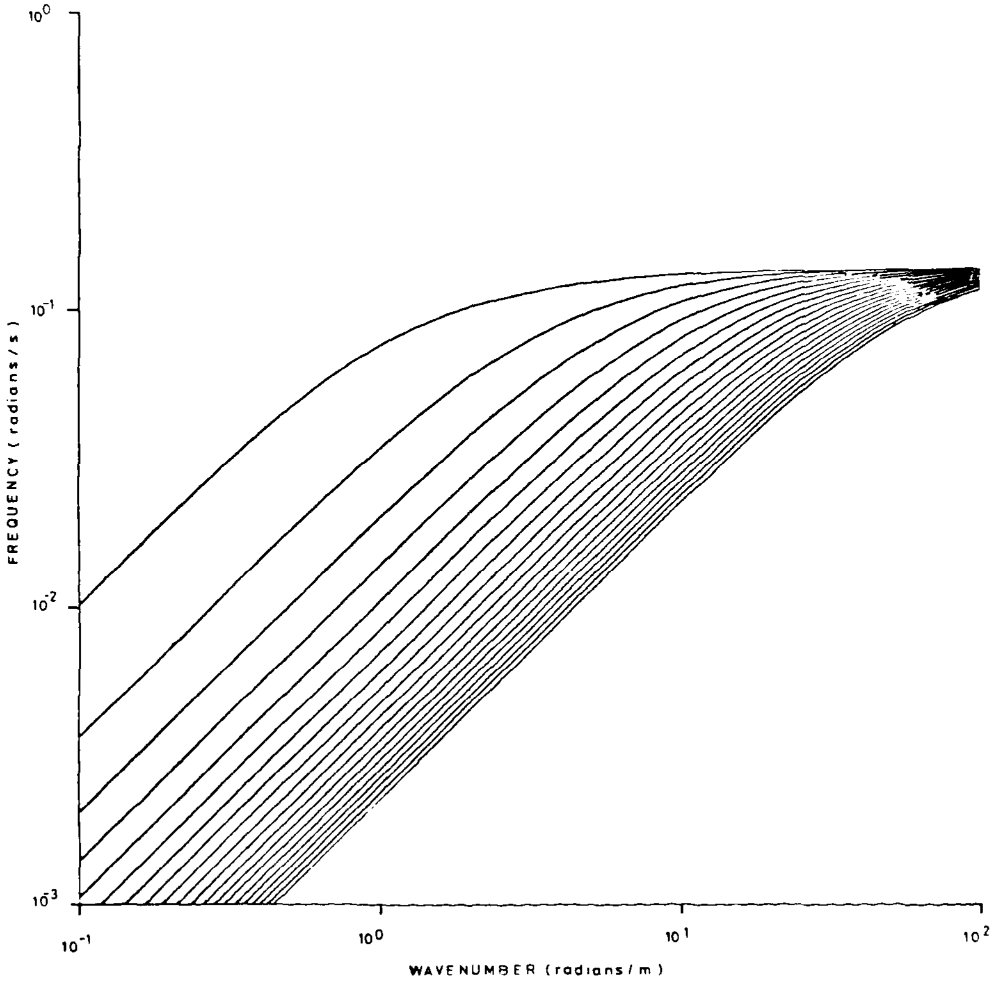


FIG. AIV-1 DISPERSION RELATIONSHIP (LOG SCALES)

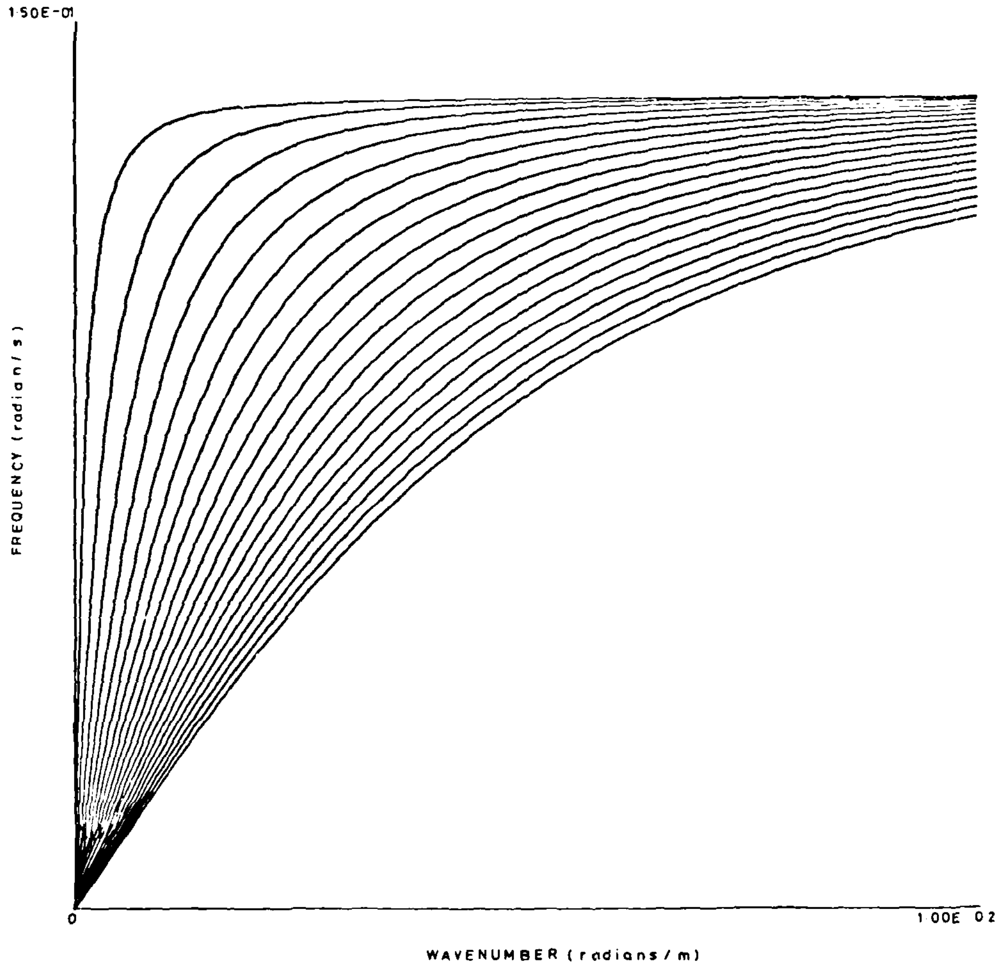


FIG AIV - 2 DISPERSION RELATIONSHIP (LINEAR SCALES)

APPENDIX V

DEVELOPMENT OF AN AUTOMATIC STRATIFYING SYSTEM

After the initial characterization tests (section 3) and the remedial measures (section 4) had been incorporated it was recognised that the manual filling method, although adequate for preliminary work, had certain shortcomings, ie (a) that to reproduce a particular profile accurately to the same buoyancy frequency value could be difficult to achieve, (b) the batch filling time was long (4 working days) whereas a continuous process at the maximum permitted rate (0.16 m/hr) would complete the fill within a 24 hour period, and (c) the process required the undivided attention of at least one member of staff during the fill. Therefore early in 1983 the advantages of automatic stratifying were considered. This was given an impetus following a visit to the Applied Physics Laboratory, Johns Hopkins University, where a smaller tank was stratified under closed-loop computer control.

During late 1983 a feasibility study* was made by Bauteil Projects Ltd, Glasgow, under contract to investigate the hardware, sensors and control necessary to provide automatically an arbitrary density profile in the Glen Fruin tank. The study considered full closed-loop control. Although a stable control system can be produced if the fill rates are sufficiently low, the study did not demonstrate conclusively that closed-loop control was feasible with the pipe runs and rates needed at Glen Fruin without the risk of a large wastage of solution. Full implementation of such a system was also considered to be expensive.

Discussions were subsequently held with Dr Richards of Loughborough University (see reference 21) who had previously stratified a tank using digital control. As a result, contact was made with Bran & Luebbe (GB) Ltd of Brixworth, Northants, who supply blending and metering pumps to the petro-chemical industry. Furthermore, the option of full closed-loop control was rejected and a more cost effective solution based on an open-loop control system was pursued. The closed-loop element of the control would be provided by measurement of the profile obtained, with corrections applied to the microprocessor control.

Having specified the maximum flowrates of the fresh water and brine likely to be required, a proposal received from Bran & Luebbe was based on a 3-headed pump unit where the stroke length on each lead was infinitely variable from zero to maximum - manually on the water head (when the unit was stationary) and adjustable by means of an electric reversing motor set by a proportional controller receiving a 4-20 mA signal from the external microprocessor for the two brine heads. The proposal reflected the envisaged operation with the water flow kept constant and the brine flowrate adjusted to the tank

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*'To investigate the feasibility of producing an automatic filling system to provide a specific profile of density with respect to depth'. Bauteil Projects Ltd, Glasgow. (January 1984).

requirement and the use of two brine heads to cover separately the 0-10% and 10% - 100% of the maximum brine flow-rate. The use of the small trim head brine pump was recommended in order to improve accuracy when very small flowrates of brine were required. The two brine heads were fitted with a lantern ring to reduce wear on the plunger and packing because of the crystalline nature of the brine solution. The dedicated microprocessor is a 6301 CMOS type programmed in FORTH by Orange Instruments of Northampton.

An outline specification of the requirements of both the hardware and software is given below.

Specification* to Bran & Luebbe (GB) Ltd

1. A typical profile of the required tank density structure is shown in Figure AV-1. This has constant density in the upper and lower layers and a linearly increasing region (over 1 metre depth) in the middle layer. However, the ability to generate arbitrary profiles of density is required.

2. Salt concentrations are measured via conductivity sensors which are sensitive to temperature, and so it will be assumed that the temperatures of the saline feed and the freshwater are constant and similar throughout the filling process. The required density profile will be specified in terms of a salinity profile ie, a weight percentage of NaCl in solution as a function of depth.

This initial profile will usually take a simple mathematical form and the typical profile shown in Figure AV-1 would be represented as three straight lines with a discontinuity in gradient at the layer boundaries (molecular diffusion, in time, 'rounds off' this boundary).

The initial profile, whether a simple linear relationship or a more complex mathematical function, should be generated in a Hewlett-Packard computer (9826) and thence transferred to the microprocessor pump-controller through an RS232 link in the form of a look up table. The corresponding data point interval should not exceed 5mm of depth. (Instrumentation has been developed to measure the density in the tank at 1mm depth intervals, ie a total of 3000 data points over the 3m depth.)

As part of the acceptance test of this initial data, the computer should calculate the pump stroke lengths required at each (or some) of the data points in the profile to check that this is within the pump capability.

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* Prepared by the first author and Dr T R Hennessy, ARE, Teddington.

3. The pumps will be as per the Bran & Luebbe proposal (ref II/20186/A, 30 July 1984), with all pumps acting in phase. The filling process will be temporarily interrupted whilst the changeover of brine pumps is achieved.

The tank is filled from the bottom through a network of filling tubes, the concentration of salt solution gradually being increased according to the required profile.

4. Absolute accuracy in achieving the desired density at any position (depth) in the profile is of less importance than the relative accuracy to adjacent points on the profile, such that the density gradient is correct. In the region of linearly varying density with depth the mean density gradient measured over a 10cm depth must be reproducible and accurate to within 0.5%

$$\text{ie } \frac{(\overline{\Delta\rho/\Delta z})\text{ measured} - (\overline{\Delta\rho/\Delta z})\text{ desired}}{(\overline{\Delta\rho/\Delta z})\text{ desired}} \leq .005$$

where Δz = 10cm.

Small jumps in density, corresponding to a depth change equivalent of 5mm or greater, are unacceptable.

5. Initial conditions, for example freshwater flowrate or saline concentration, may vary from fill to fill even though the profile required may be similar.

6. It is assumed that the 2000 gallon storage tank shown in Figure 8 will be the source of the concentrated saline solution. If for any reason this is not possible, then several batches of saline feed would have to be made in the small mixing tank. The fill up process would have to be interrupted and the feed concentration corrected.

7. Ability to override the software controller and switch back to manual control is needed if faults develop. In this case, manual operation of the brine pumphead stroke should be possible.

8. A fail safe operation is needed - should there be a component failure, the process must shut down and produces a warning. In the event of a power cut, the volume pumped should be stored in a non-volatile memory. The possibility of a 'warm' start, with a part filled tank should be acommodated, ie it should request the current state of the fill and whether new feeds and new profile parameters are required.

9. The nominal flowrates of freshwater and a calculation method for the brine flowrate are as follows:

tank dimensions: 9m x 3m x 3m (approximate)

capacity: $81m^3$ (=18000 gallons);

for filling in 24 hrs, approximate flowrate = 0.94 l/s (=750 igph);

saline feedstock is typically about 10% wt solution of NaCl with a S.G. of about 1.07;

For the very weak saline solutions required in the tank, the specific gravity of the solution can be related to the percentage by weight of NaCl in solution by

$$S.G. = 1 + .007W,$$

where W is the % by weight of NaCl in solution and does not exceed 10%.

Let the flowrate of freshwater, which is constant throughout the fillup, be denoted by F_w (blending/mixing is achieved by varying the flowrate of the saline feed). Let the % by weight of NaCl in the feedstock be denoted by W_f and that of the required solution for the tank at any particular depth of fill, z, be W_t. Then the required flowrate of saline feedstock of W_f% (by weight) is given by

$$F_s = \frac{F_w W_t}{W_f - W_t},$$

ie, as concentration of saline feed decreases the flowrate of NaCl solution becomes more non-linear with depth of fill (for a linear profile). However, for the relatively weak solution required (W_t), F_s is approximately linear with depth.

For the typical density profiles required for which $\Delta\rho$ is constant over 1 metre depth, the salt content varies between 1.47 kgm^{-3} to 5.87 kgm^{-3}.

If the top layer is freshwater with a S.G. of 1.00, the S.G. of the bottom layer for the largest variation is 1.00587. This corresponds to a % by weight of NaCl of 0.83%

Therefore, the maximum flowrate of brine of 10% by weight feedstock is

$$\frac{0.94 \times 0.0083}{0.1 - .0083} = 0.085 \text{ l/s} \quad (= 67.9 \text{ igph}).$$

10. To simplify control, it is suggested that the flow of freshwater be kept constant throughout a fill. (NB The freshwater pump is fitted with a manual stroke adjustment only). The flow of concentrated brine being increased with fill to achieve the required blend.

11. The tank is assumed to have constant plan area with depth so that the depth of fill, and hence the brine flow required, can be determined from the total volume pumped.

12. It should be possible to input different types of profile easily.

13. To provide the 'closed-loop' control for the filling process, it is necessary to compare the profile achieved with that desired. Calculation of an error profile together with the flowrate-time history on each pump should highlight the cause of any discrepancy. A strategy for adjusting (in both the direction

and magnitude) the potentiometers on the pump controller should be presented.

14. The software should allow a freshwater flowrate of the order of 1300 igph (compared to the 750 igph at Glen Fruin) to allow for future development.

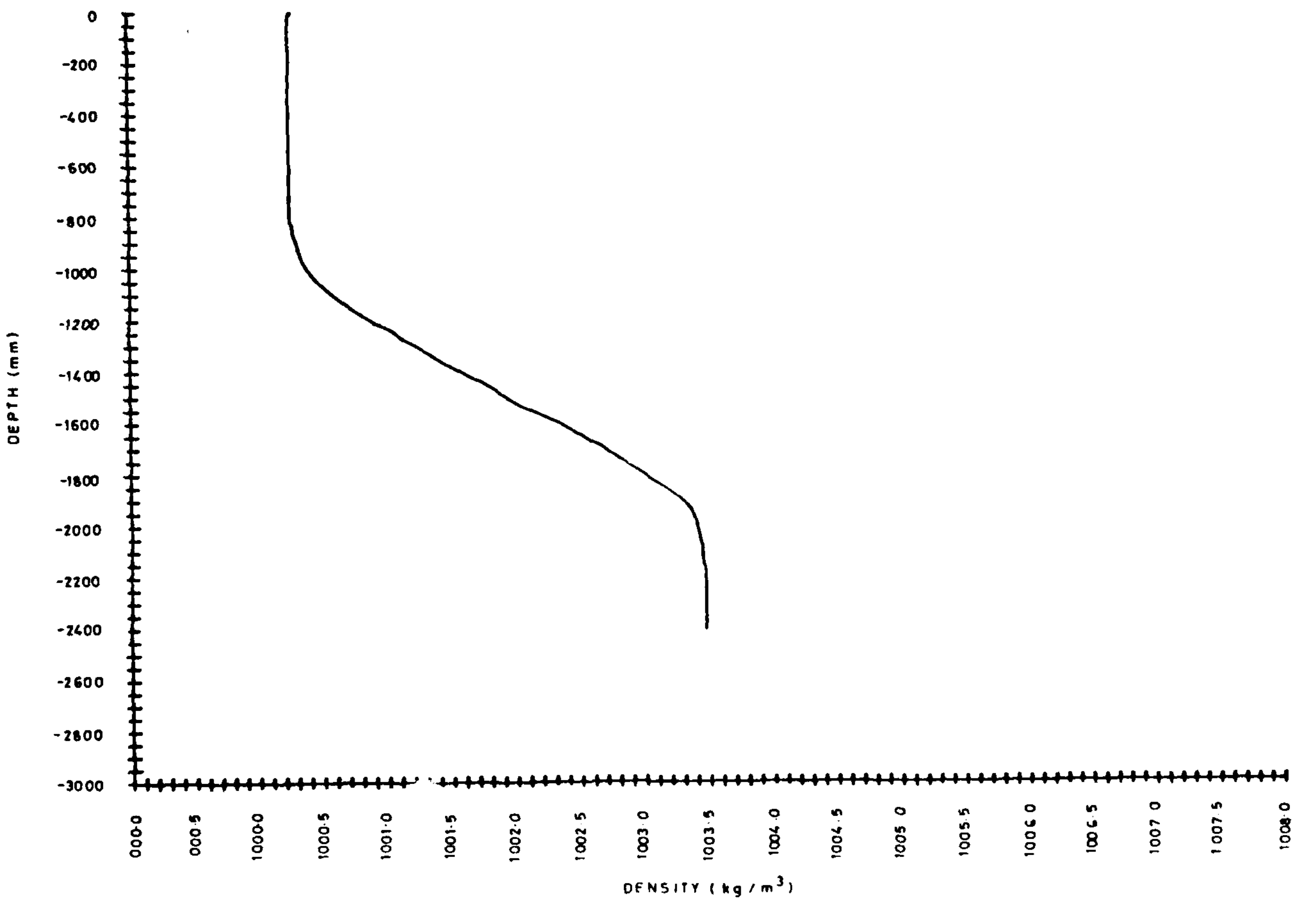

FIG A V-1 TYPICAL DENSITY PROFILE

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